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METHANE-AIR EXPLOSION TESTS IN THE 20-L VESSEL

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by

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ABSTRACT

Quiescent and turbulent explosion tests were carried out on methane-air mixtures in order to "calibrate" the 20-L vessel that is used for dust explosion measurements. The quiescent tests showed that the use of either a too weak or a too strong ignition source leads to significant errors in determining the lower flammability limit. Use of Sobbe pyrotechnic ignitors caused a slight underestimate of the explosion pressure and a substantial underestimate of the rate of pressure rise.

Experimental evidence shows that, due to the rate of air entering the vessel during a normal dust explosion test, the actual concentration of air is about 15% less than that indicated by the instantaneous pressure measurement at the time of ignition. Since explosion pressure is directly proportional to concentration, measured explosion pressures must be increased by that factor. The results obtained for methane-air explosions under these conditions supported this argument.

The turbulence created in a typical dust explosion test increased the explosion pressure of methane by only about 4%, but tripled the rate of pressure rise.

KEYWORDS: Explosions, methane, flammability limit

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ESSAIS D'EXPLOSION DE MÉLANGES MÉTHANE-AIR DANS LE RÉCIPIENT DE 20 L

par

K.J. Mintz*

RÉSUMÉ

Des essais d'explosion de mélanges méthane-air, au repos et turbulents, ont été menés pour étalonner" le récipient de 20 L qui est utilisé pour les mesures sur les explosions de poussières. Les essais sur les mélanges au repos ont révélé que l'utilisation d'une source d'inflammation soit trop faible, soit trop puissante, entraine des erreurs importantes dans l'évaluation de la limite d'inflammabilité. L'utilisation d'amorces pyrotechniques Sobbe s'est traduite par une légère sous-estimation de la pression d'explosion et par une importante sous-estimation de la vitesse de montée de la pression.

Les résultats experimentaux montrent qu'a cause de la vitesse d'entrée de l'air dans le récipient pendant un essai normal d'explosion d'une poussière, la concentration réelle d'air est d'environ 15% inférieure à celle indiquée par la mesure de la pression instantanée au moment de l'inflammation. Comme la pression d'explosion est directement proportionnelle à la concentration, les pressions d'explosions mesurée doivent être augmentée de ce facteur. Les résultats obtenus pour les explosions de mélanges méthane-air dans ces conditions confirment cette affirmation.

La turbulence établie dans un essai d'explosion de poussière type a élevée la pression d'explosion du méthane d'à peine 4% environ, mais a fait tripler la vitesse de montée de la pression.

MOTS CLÉS: explosions, méthane, limite d'inflammabilité

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INTRODUCTION

The U.S. Bureau of Mines type of 20-L explosion test vessel has been used for a number of investigations of dust explosibilities during the past two years in the Canadian Explosive Atmospheres Laboratory (CEAL). Types of dusts tested at the request of industries have been propellants, plastics, fertilizers, sulphide ores, coals, aluminum, and petroleum cokes. The commissioning of the vessel in 1988 (1) was based on tests carried out on lycopodium powder, which is often used as a "standard" dust.

In 1988, the American Society for Testing and Materials (ASTM) published a standard on measuring the maximum explosion pressure, P_{max}, and the maximum rate of pressure rise, $(dP/dt)_{max}$ in near-spherical laboratory chambers of volume 20 L or greater (2). The specification of 20 L as the minimum size is based on comparison with a range of larger and smaller vessels. A number of different 20-L vessels are in use. Only one, however, the Siwek apparatus developed by CIBA-Geigy (Switzerland) has been calibrated and accepted by the ASTM Committee[2]. The ASTM Committee is currently carrying out a round-robin test of P_{max} and $(dP/dt)_{max}$ in other vessels, using various "standard dusts". Eventually the ASTM committee will issue standards for other explosibility parameters, e.g. minimum explosible concentration (MEC), as well.

The major difficulty of laboratory measurements of dust explosions is the effect of turbulence. Turbulence is usually required to create a dust cloud[3], in contrast to a gas mixture, which can easily be studied under quiescent conditions. In order to be able to properly calibrate an explosion vessel, including the separation of the effect of turbulence, it is beneficial to use a well-known gas system, e.g. methane-air, to study explosions in that vessel.

Hertzberg et al (5)studied the effect of ignitor strength on the lower flammability limit[4], P_{max} and $(dP/dt)_{max}$ using quiescent methane/air mixtures in

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[2]This vessel is very similar, except in size, to the 1 m^3 vessel used extensively by Bartknecht (3). Bartknecht's vessel is used as the basis of the International Standard on dust explosibility (4).

[3]The writer is aware of only one dust explosibility apparatus which does not require turbulence for dispersion, the tapping sieve apparatus used by a couple of researchers in Japan. This apparatus can only be used for the determination of MEC, not P_{max}.

[4]In accordance with the usual practice, the term "lower flammability limit" (LFL) is used for gases and is measured in volume %, and the term minimum explosible concentration (MEC) is used for dusts and is measured in g/m^3.

the 20-L vessel. Using 500 and 1000 J Sobbe ignitors yielded a LFL of 4.9 ± 0.1 %, in close agreement with the accepted value of 5.0%. However, they found that using a "strong" ignitor (2500-J Sobbe pyrotechnic ignitor[5]), the flammability limits were widened significantly. This effect was attributed to overdriving the reaction. Using their criteria that the explosion pressure ratio be ≥2 and the volume-normalized rate of pressure rise be ≥1.5 bar·m/s, the LFL was 4.4%. (Using only the first criterion would yield a LFL of 4.0%.) Using a capacitive discharge of stored energy 17 J yielded a higher than normal LFL, 5.5%. In this case, the ignitor was clearly of inadequate strength.

In addition, Hertzberg et al found that both the pressure ratio and pressure rise rate were higher for the spark than for even the weakest Sobbe ignitor (500 J). This was attributed to differences in the ignition source geometry causing the Sobbe ignitor to cause a less adiabatic (i.e. less "ideal") explosion.

The present study was undertaken to reproduce the work by Hertzberg et al on quiescent methane-air mixtures and extend it to turbulent methane-air mixtures produced in a similar way as the dust tests. A further study will then be carried out on "standard" dusts.

An additional impetus to making this study was the 4% value for the LFL of methane obtained by a contractor (6) as part of a study of the effect of methane on the explosibility of Cape Breton Development Corporation coal dust. This value was obtained in a 26-L vessel using a 5000-J Sobbe ignitor. The low LFL was attributed to overdrive. However, it calls into question whether explosion tests on hybrid gas-dust mixtures or even on dust alone were also overdriven.

EXPERIMENTAL PROCEDURE

The apparatus used for the explosion tests, the 20-L vessel and associated equipment, was the same as used in the previous study (1), except that a stainless steel thermocouple was installed and the output from it fed into the storage digital oscilloscope along with the pressure. Although this

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[5]The effective energy of the Sobbe ignitors, according to the work by Hertzberg et al (5), is actually only about half of the nominal energy quoted.

does not yield the true temperature of explosion, it does provide additional confirmation whether or not an explosion has occurred.

A Beckmann infrared analyzer was used to measure the concentration of methane in prepared methane-air mixtures. A calibration chart for 0 - 10% methane was constructed by using the CEAL binary mixer to make up methane-air mixtures from technical grade methane and bottled dry air. The analyzer was adjusted frequently using dry air for the zero and a 2.55% methane/air mixture for the gain. In a few tests, the quantity of methane remaining after the test was measured by pumping a part of the contents through the analyzer.

The terms used in this report will correspond to those of the ASTM Standard:

P_{ex} - the maximum explosion pressure in an individual test, after taking into account the initial pressure in the vessel and the pressure due to the chemical ignitor.

P_{max} - the maximum explosion pressure of a particular material, based on the P_{ex} determined over the optimum concentration range.

$(dP/dt)_{ex}$ - the maximum rate of pressure in an individual test.

$(dP/dt)_{max}$ - the maximum rate of pressure rise of a particular material, based on the $(dP/dt)_{max}$ determined over the optimum concentration range.

RESULTS

PART I: QUIESCENT MIXTURES

Arc Ignitor

The pressure traces of the tests using the arc ignitor are shown in Fig. 1 - 6. In most of the trials, spikes can be observed in the pressure traces due to pick-up from the spark discharge. (In many of the trials, the spikes can be observed only under amplification of the ordinate axis, and therefore do not show on the figures.) Time zero is set as the time of the first spike. Trials using 5.1 and 5.3% methane did not produce a sufficient pressure rise to trigger the oscilloscope and therefore no pressure trace was obtained. With 5.1% methane, no flame was observed; 3.5% methane was measured after the test, indicating that, in fact, a small amount of reaction did occur. Similarly, with 5.3% methane, a very small, weak flame was seen at the spark electrodes. This flame went upwards, then extinguished itself; 4.0% methane was measured after the test. The criteria developed by the U.S. Bureau of

Mines for a "true" explosion is that the P_{ex} be twice the initial pressure and the K_G be 1.5 bar·m/s. In our system, that translates into a minimum of 101 kPa for P_{ex} and 500 kPa/s for $(dP/dt)_{ex}$. These criteria indicate that 5.5% methane produced a marginal explosion, but 5.9% produced a definite explosion, even though the course of the explosion was clearly irregular (Fig. 1). In both cases, no flame was observed, but with 5.5% methane, there was still 3.2% methane remaining after the test, whereas with 5.9% methane, only 0.5% methane was left. The trial with 6.3% methane showed a break in the pressure trace near the maximum. An orange flame was observed, and only 0.3% methane was left. At progressively higher concentrations of methane, the flame became brighter and the amount of methane decreased to zero. The sharp break in the pressure trace remained for most of the tests, though it usually occurred after the maximum. For several trials, strong oscillations occurred, particularly near the maximum. These oscillations had a frequency of about 250 Hz.

It is difficult to ensure that the pressure at the time of ignition is precisely 101.2 kPa, which is required for strict comparability of data. This is especially true for dust experiments where the back pressure of dust in the chamber affects the rate of air ingress. There are two ways that are commonly used to take that problem into account. One way is simply to ensure that all tests are within, say, 10% of one atmosphere pressure. The difficulty with that method is that it may cause a systematic error in the data. Another method is to use pressure ratios, rather than the actual pressure. An alternative to both of these methods (and one which is used in this laboratory), is to apply the accepted linear relationship between P_{ex} and initial pressure. Thus, the corrected P_{ex} is given by the following equation:

$$P_{ex} = \frac{1.0}{P_i} \times P_{ex}(\text{uncorrected})$$

where P_i is the pressure at the time of ignition. All values of P_{ex} in this and preceding reports refer to these corrected values. The conditions of the tests are selected to be close to one atmosphere; this correction is almost always less than 5%, even for the dust explosion tests.

The data on P_{ex} from all the spark ignition tests is shown in Fig. 7. From this curve, P_{max} is estimated to be 700 ± 10 g/m^3, slightly smaller than the value of 720 g/m^3 obtained by Hertzberg with a spark ignition source (5).

However, the latter used a single electric spark, our tests used a weaker, continuous discharge.

The derivatives of four pressure traces are shown in Fig. 8 - 11. The abscissa scale is the same for all four graphs, but the ordinate scales are different. The graphs for 5.5% and 5.9% methane (Fig. 8 and 9) are quite similar; in both cases, the $(dP/dt)_{ex}$ is below the U.S. Bureau of Mines criterion for self-sustaining explosion (500 kPa/s). There is a qualitative change in the derivative curve between 5.9% and 6.3% methane (Fig. 10). The latter is essentially a single peak (not counting the peaks due to the electric discharge). At the optimum concentration (Fig. 11), the shape of the curve is essentially the same, but narrower and higher.

The values of $(dP/dt)_{ex}$ are plotted in Fig. 12. The scatter is slightly greater than the data of Fig. 7, because of the errors involved in numerical differentiation. The value of $(dP/dt)_{max}$ determined from this plot is 24,200 ± 600 kPa/s, corresponding to a K_G of 65 ± 2 bar·m/s, close to Hertzberg's value of 68 bar·m/s as read off their graph (5).

The LFL is, in this case, governed by the $(dP/dt)_{ex}$, rather than by the P_{ex}. The value is 5.9 ± 0.2 %, slightly higher than the value of 5.5%, from the graph of Hertzberg et al (5). It should be noted, however, that the more energetic spark, used by the latter, would be expected to have more of an effect on the LEL than on the other explosion parameters.

The "temperature rise" data, shown in Fig. 13, indicates that the test with 5.9% methane produced a full explosion, whereas the $(dP/dt)_{ex}$ data indicates that test was not a full explosion. Recall also that the P_{ex} data did satisfy the criterion in this trial.

Sobbe Ignitors

Figures 14 and 15 show some of the pressure traces in explosion tests using 250-J Sobbe pyrotechnic ignitors. This ignitor generates a pressure of about 9 kPa when ignited in an empty vessel. It is clear that the pressure trace for 4.9% methane is essentially all due to the ignitor. The other pressure traces are smooth and show a definite peak due to the methane-air explosion. The contrast with Fig. 1 which showed the pressure traces on tests with the arc ignitor (the scales for the abscissae are the same) indicates that the boundary between non-explosibility and explosibility is much sharper when the 250-J ignitor is used than when the arc is used. This indicates that the

arc does not provide sufficient energy into the methane-air system to produce a true flammability limit. Figure 15 shows pressure traces closer to the optimum concentration. (Note that the absicca is expanded, and the ordinate contracted, relative to Fig. 14.) The peak pressure increases and the time to the maximum decreases as the optimum concentration is approached. The test with 11.7% methane is on the fuel-rich side of stoichiometry and thus the explosion is weaker. The reason for the large oscillations near the maximum of the trace for 8.9% methane is unknown.

Since the pressure developed by the 250-J Sobbe ignitor in the 20-L vessel is very small (9 kPa), P_{ex} was determined simply by subtracting that value from the experimental maximum pressure in each trial.

The derivative of the pressure trace for the test with 5.7% methane is shown in Fig. 16. The sharp peak which occurred at t = 0 s is due to the ignitor. In this example, the peak due to the ignitor was fairly well separated from that due to the methane-air explosion. As the concentration of methane approaches the optimum, however, the peak due to the explosion moves closer to that of the ignitor and separate peaks are no longer observed. Fortunately, there is no problem with the determination of $(dP/dt)_{ex}$ because the ignitor peak width is very narrow relative to the peak width of the methane explosion.

All the data for P_{ex} with the 250-J Sobbe are shown in Fig. 17 (open circles); the data for $(dP/dt)_{ex}$ are shown in Fig. 18 (also open circles). There is a clear cut-off at the LFL, in contrast to the tests carried out with the arc ignitor (Fig. 7). The value of the LFL is 5.1 ± 0.1% which is in good agreement with the accepted literature value of 5.0%, and also with Hertzberg's value of 4.9 ± 0.1% measured in the 20-L vessel using 500-J Sobbe ignitors(5), but which is significantly lower than the value of 5.9 ± 0.2% measured using the arc ignitor.

The value of P_{max} using the 250-J ignitor was 680 ± 20 kPa, slightly less than that determined from the arc ignitor tests. It is the same value obtained by Hertzberg in the 20-L vessel, using 500-J ignitors. Hertzberg attributes the lower value of P_{max} obtained with the pyrotechnic ignitors to it being a non-point source and thus causing a less adiabatic reaction.

The value of $(dP/dt)_{max}$ using the 250-J ignitor was 15 000 kPa/s, corresponding to a K_{St} of 41 ± 3 bar·m/s. Although this value is much lower than the value of 65 ± 2 bar·m/s obtained with the arc ignitor, it is close to

the value of 45 bar·m/s obtained by Hertzberg (5) using 500-J ignitors. Three traces of tests carried out with the 5000-J Sobbe ignitor are shown in Fig. 19 along with the pressure trace due to the ignitor alone. Clearly, the pressure developed by this ignitor is significant in the 20-L vessel. The correction method used for the 250-J Sobbe ignitor may not be sufficiently accurate for the 5000-J Sobbe. Instead, the pressure trace due to the ignitor alone was subtracted from the experimental trace; the maximum of the resultant trace is, to a sufficiently good approximation, P_{ex} (after correcting it to one atmosphere pressure, as discussed above).

The values of P_{ex} for the 5000-J Sobbe are shown in Fig. 17 (filled circles). There is a rather gradual rise in P_{ex} starting from about 2% methane. Using Hertzberg's criterion, the LFL would be at about 2.4%, well below the value measured from the 250-J Sobbe of 5.1 ± .1% and the accepted value in the literature of 5%.

The value of P_{max} determined using the 5000-J ignitor is significantly less than the P_{max} determined using the 250-J ignitor (see Fig. 17). One test was carried out using a 1000-J ignitor at the optimum concentration (shown as the triangle in Fig. 17). The value of P_{max} was between the other two values, adding support to the concept that P_{max} is a function of ignitor strength.

Surprisingly, the values of $(dP/dt)_{ex}$ for the 5000-J ignitor (filled circles in Fig. 18) are much greater than the corresponding values for the 250-J ignitor. Hertzberg (5) did not present any data for $(dP/dt)_{ex}$ in the optimum range with high-energy ignitors, therefore, no comparison with the literature can be made. It is likely that the large values are due to overdriving.

The temperature rise data for the tests carried out with the 250, 1000 and 5000-J ignitors are shown in Fig. 20. The ignitors alone cause a temperature rise of 4°C for the 250-J and 25°C for the 5000-J. The maximum temperature with the 250-J ignitor was about the same as that produced by the arc ignitor (see Fig. 13). The 5000-J ignitor produced a greater temperature rise, but after compensating for the rise due to the ignitor, the temperature rise due to the explosion is only slightly greater.

Measurement of the oxygen concentration in the vessel after an explosion test allowed determination of the percent of oxygen consumed in that test. The data for all the tests in which oxygen was measured are shown in Fig. 21. The data points fall on a straight line (except for the concentra-

tions at which no "true" explosion occurred). The lines extrapolate to between 0 and 1% CH_4 on one end and close to the stoichiometric mixture at the other end. Furthermore, since the concentration of methane after the test was measured (and usually found to be close to zero), the mass balance of the system can be determined. In most of the trials, the quantity of methane consumed was within 5% of twice the quantity of oxygen consumed. This is consistent with the reaction:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

PART II: TURBULENT MIXTURES

Calibration of Air Concentration

In a dust explosion test in the 20-L vessel, the first stage is to open a solenoid to allow air to enter the previously-evacuated vessel from a 16-L tank holding air at a pressure usually of about 11 - 13 bar. This air enters very quickly, to reach about one bar in about 300 ms. During this process, and for some period afterwards, the air is not at thermal equilibrium and therefore it does not have a definable temperature. In addition, of course, the air is turbulent.

In the explosion tests on quiescent methane/air mixtures, a correction was made to allow all P_{ex} to be expressed for a pressure of one bar. The correction factor was based on a substantial body of evidence that explosion pressure is directly proportional to the initial pressure at constant temperature. In addition, explosion pressure has been found to be directly proportional to the inverse of the absolute temperature, at constant initial pressure (7). In both relationships, the fundamental property is really the initial concentration, i.e. those two relationships can be combined to state that the explosion pressure is directly proportional to the initial concentration.

In the case of the air entering the vessel rapidly, the concentration cannot simply be assumed to be proportional to the pressure, for the reasons given above. Although a direct method of measuring the air concentration is possible, it would be somewhat difficult because of the rapid change involved. A much simpler approach is to wait until the system has reached equilibrium; the mean concentration must remain constant once the solenoid valve has closed.

Thirteen tests were carried out, using two different tank pressures (to provide two different flow rates) and several different solenoid valve open times (to provide different final pressures, P_{final}). In all cases, the pressures increased rapidly until the solenoid valve closed then decreased slowly, reaching constant values after 15 - 70 s. The highest pressure reached is designated P_{air}. The results are shown in Fig. 22. Note that the ordinate is greatly expanded. The maximum air pressure and the tank pressure seem to have only a very slight affect on the P_{air}/P_{final} ratio.

In the procedure used by the U.S. Bureau of Mines, the 20-L vessel is only partially evacuated, to 0.2 bar. Amyotte et al evacuated their vessel to 0.53 bar prior to conducting their tests. Therefore, it was of interest to determine the effect that partial, rather than full, evacuation has on the P_{air}/P_{final} ratio. Three tests were carried out with P_{air} about 130 kPa and the tank pressure of 1100 kPa. For an initial pressure of 0.1 bar, the ratio was 1.175 (essentially unchanged) and for initial pressures of 0.3 and 0.5 bar, the ratio decreased slightly, to 1.15. (The ratio must approach unity as the quantity of air added decreases towards zero.)

In view of the argument presented above, the measured P_{ex} must be multiplied by $1/P_{final}$ (P in bar) to determine the explosion pressure valid at one bar. However, it is impossible to measure P_{final} in an explosion test. Because the P_{air}/P_{final} ratio has been shown to be very reproducible, the following relationship can be used to determine the correction factor:

$$\frac{1.0}{P_{final}} = \frac{1.0}{P_{air}} \times \frac{P_{air}}{P_{final}}$$

Most explosion tests are carried out at about one bar; therefore, from the graph, the P_{air}/P_{final} ratio of 1.17 ± 0.01 and 1.18 ± 0.01 should be used for tank pressures of 1100 and 1300 kPa, respectively.

The implication of this section is that explosion tests carried out at apparently one bar have actually been carried out at the equivalent of about 0.85 bar, and thus a correction factor must be applied to the observed values of P_{ex}.

Arc Ignitor

In order to measure the effect of the type of turbulence normally associated with dust explosion tests in the 20-L vessel, methane-air explosions were carried out in a similar manner to dust explosion tests. First, methane was added to the vessel, then the trial carried out as usual, i.e., the solenoid was opened for the usual length of time so that the air pressure would be approximately one bar, and then the ignitor was fired after a preset delay. The implicit assumption is that the addition of air would be sufficiently turbulent that a homogeneous mixture would be generated, which is equivalent to the assumption that the action of the air is sufficient to create a homogeneous dust cloud. The quantity of methane added was such as to yield an approximately stoichiometric mixture. (The tests reported in Part I showed that the arc ignitor can not be used for determining flammability limits but only for P_{max} and $(dP/dt)_{max}$.)

The experimental explosion pressures were corrected to one bar using the procedure in the previous section, and plotted as a function of time delay to ignition, ie. the time between the solenoid closing and the beginning of the arc discharge (Fig. 23). P_{max} to reach an asymptotic value of about 700 ± 10 kPa. This is the same value measured in the quiescent explosion tests[6].

Similarly, Fig. 24 shows the rate of pressure rise as a function of delay time. In this case, it is more difficult to estimate a precise asymptotic value to compare to the quiescent value of 24 200 kPa/s.

The present work shows that turbulence has a much greater effect on $(dP/dt)_{max}$ than P_{ex}, which is in agreement with other studies (3). The graphs indicate that the turbulence from a typical explosion test in the 20-L vessel dissipates in about two seconds. In dust explosion tests, the time delay is usually selected to be about 100 ms, in order to prevent significant gravitational settling. At such a time delay, there would certainly be a contribution from turbulence to the magnitude of the dust explosion parameters. If it were assumed that the increase for dust explosions due to turbulence were similar to that of methane, then the "zero turbulence" P_{max} would be about 4% smaller,

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[6] If the correction factor were not included, then the value of P_{max} would be only 600 kPa, which would be in substantial disagreement with the quiescent and literature values. This is, in fact, the major experimental proof of the analysis presented above.

which is less than the normal scatter of data. On the other hand, the zero turbulence $(dP/dt)_{max}$ would be about 34% of the experimental value.

One test at a delay time of 124 ms was carried out using a 250-J Sobbe ignitor, which produced a corrected P_{max} of 684 kPa and a $(dP/dt)_{max}$ of 25700 kPa/s. Both of these are lower than those determined using the arc ignitor, following the same pattern as observed for the quiescent explosion tests.

LEL - Sobbe Ignitors

Near-limit flammable methane-air mixtures were produced in the high-pressure storage vessel by the partial pressure method. The actual percentage of methane in the mixture was measured by the Beckmann analyzer. The rest of the procedure was carried out as in the standard procedure for dust explosion tests. 250-J Sobbe ignitors were used because they had been found to provide the most meaningful data (see p.6). Two different levels of turbulence, representing the extreme possibilities were produced by using two different ignition delay times, specifically 20 ms and 570 ms. The data for P_{ex} and $(dP/dt)_{ex}$ are shown in Fig. 25 and 26, respectively. The LEL for the low turbulence mixture was 4.8 ± .1 %, for the high turbulence mixture, 4.9 ± 0.1 %. These values are only slightly lower than that obtained in the quiescent mixture (5.1 ± .1 %), and are close to the accepted value of 5.0%.

CONCLUSIONS

The lower flammability limit of methane has been shown to be a function of the ignitor energy used in the 20-L vessel. If too low an energy is used (e.g. a continuous discharge), then the LEL will be significantly higher than the accepted value. If too large an energy is used (e.g. 5000-J Sobbe), then the LEL will be considerably too small. The shape of the P_{ex} vs. concentration curve for any given ignitor provides an indication of the suitability of the strength of that ignitor.

The electric discharge yielded P_{max} and $(dP/dt)_{ex}$ for methane in good agreement with literature data. Use of the weakest Sobbe ignitor yielded a slightly lower value for P_{max} and a substantially lower value for $(dP/dt)_{max}$.

Explosion tests of methane in the 20-L vessel, carried out using a similar procedure as used for dust explosion tests, yielded an apparent P_{max}

significantly smaller than tests carried out in a quiescent state. This was shown to be due to non-equilibrium effects from the air entering the vessel. When a correction was made for this effect, the discrepancy was eliminated. Dust explosion tests will also require the same correction.

Using the same levels of turbulence as used normally in dust explosion testing did not produce any significant change in the LEL of methane, but caused a slight increase in P_{max} and a very large increase in $(dP/dt)_{max}$.

Explosion tests will be carried out on lycopodium powder and standard Pittsburgh coal dust to determine whether these correction factors can account for discrepancies in P_{max}. In addition, the effect of ignitor energy on the explosion parameters will be studied to determine if the effect on dusts is similar to that of methane.

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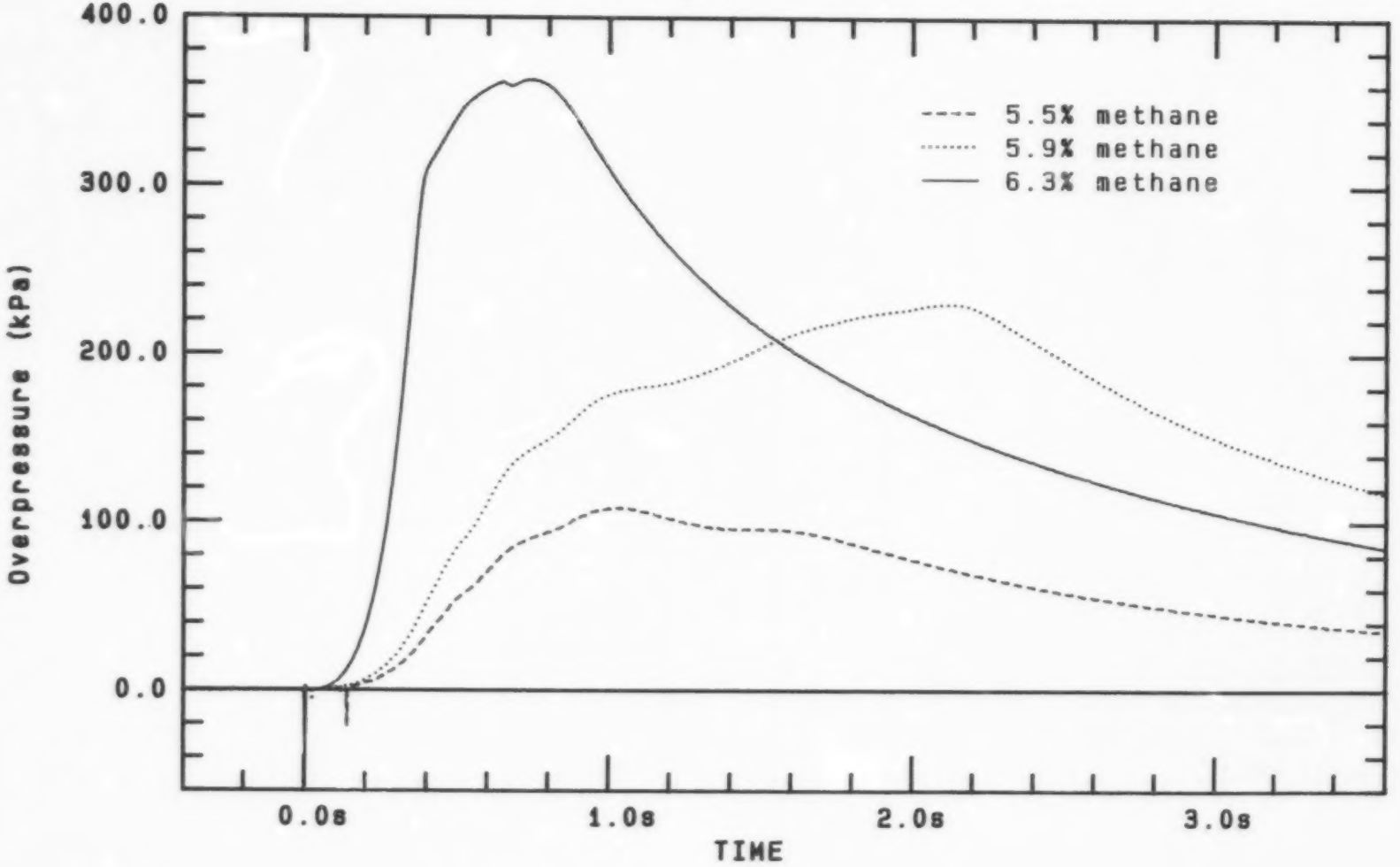
Fig.1. Pressure Traces for Methane-Air Explosions:

Arc Ignitor Used



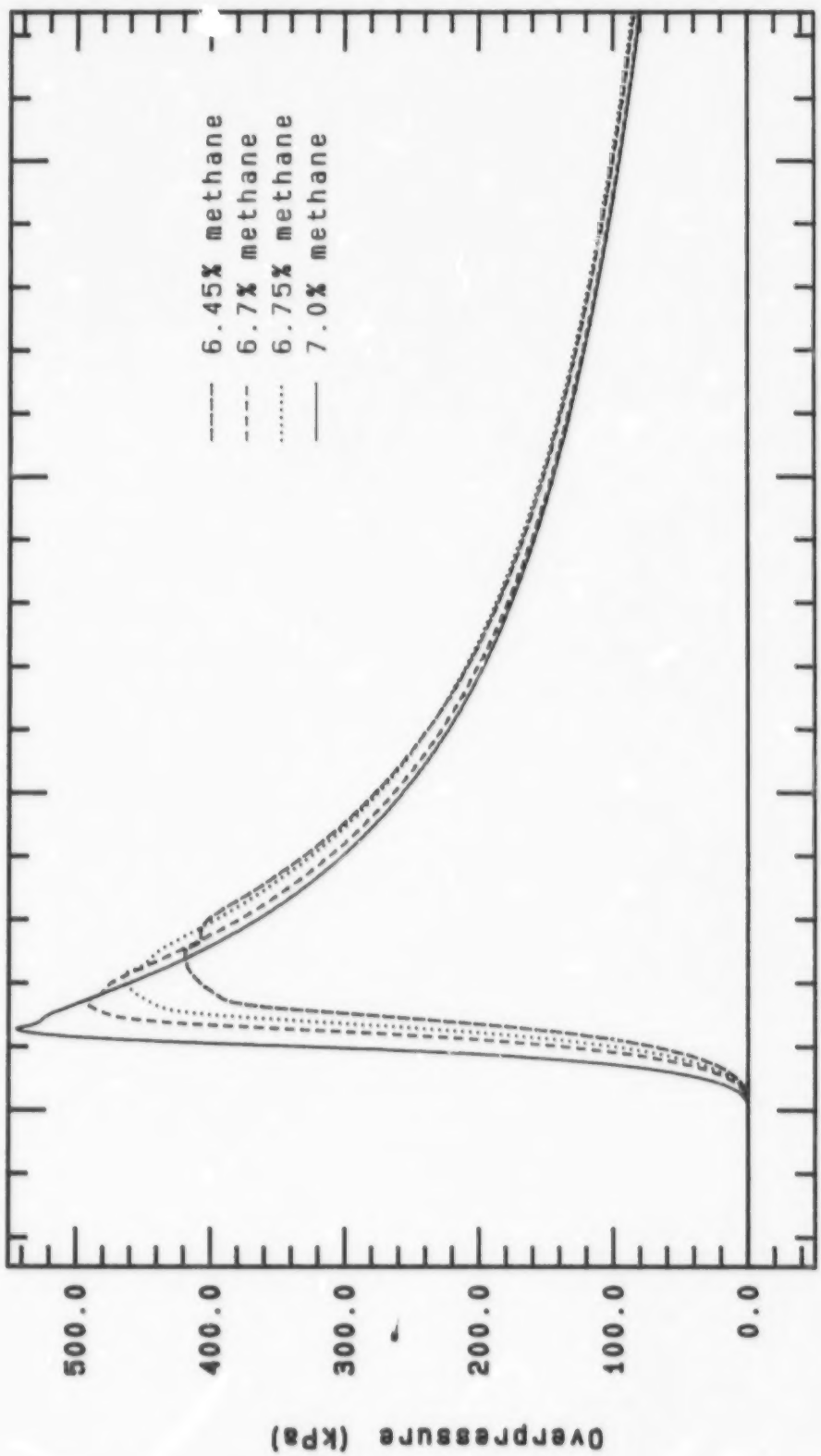


Fig.2 Pressure Traces for Methane-Air Explosions:

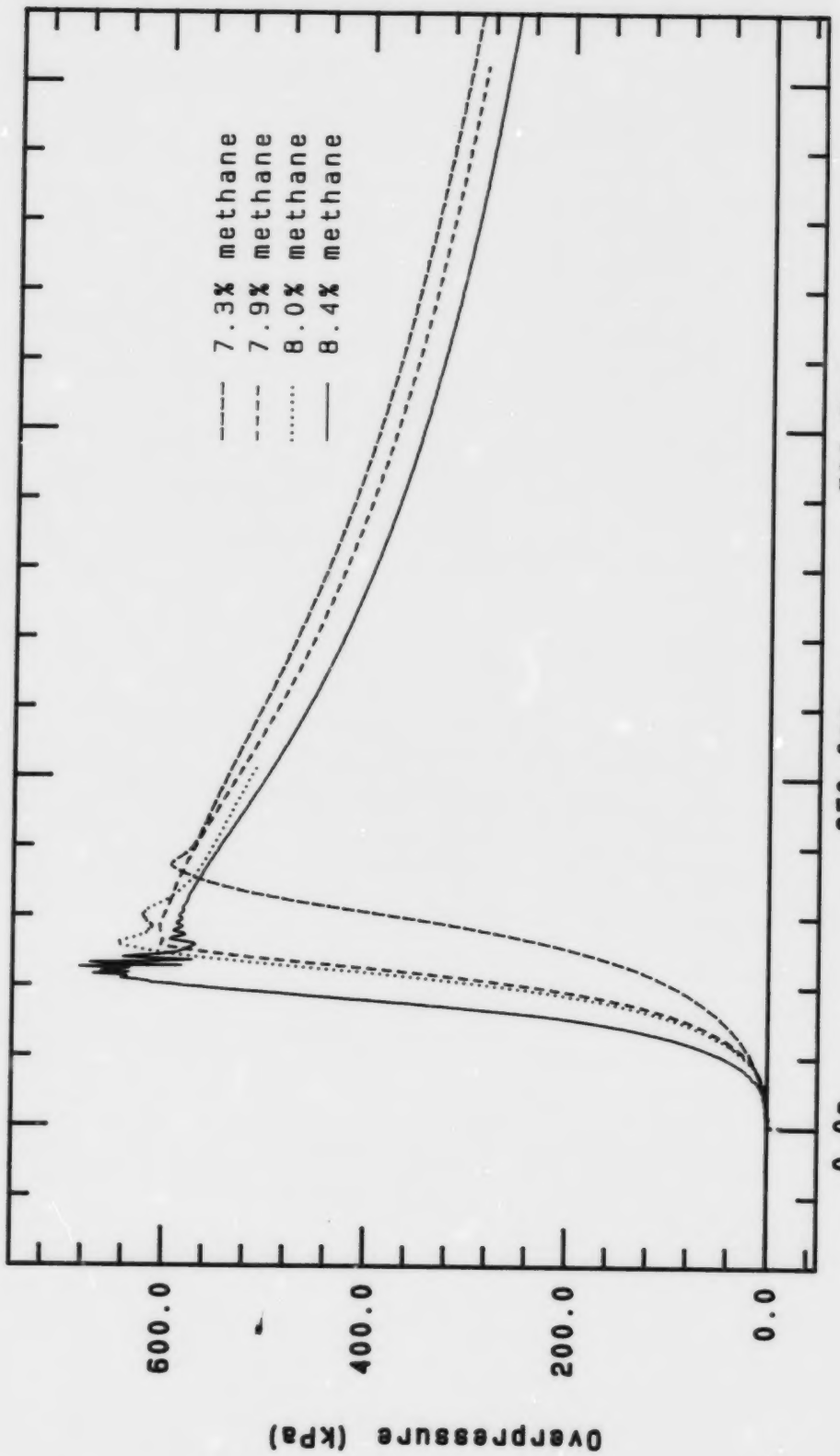


Fig.3. Pressure Traces for Methane-Air Explosions:

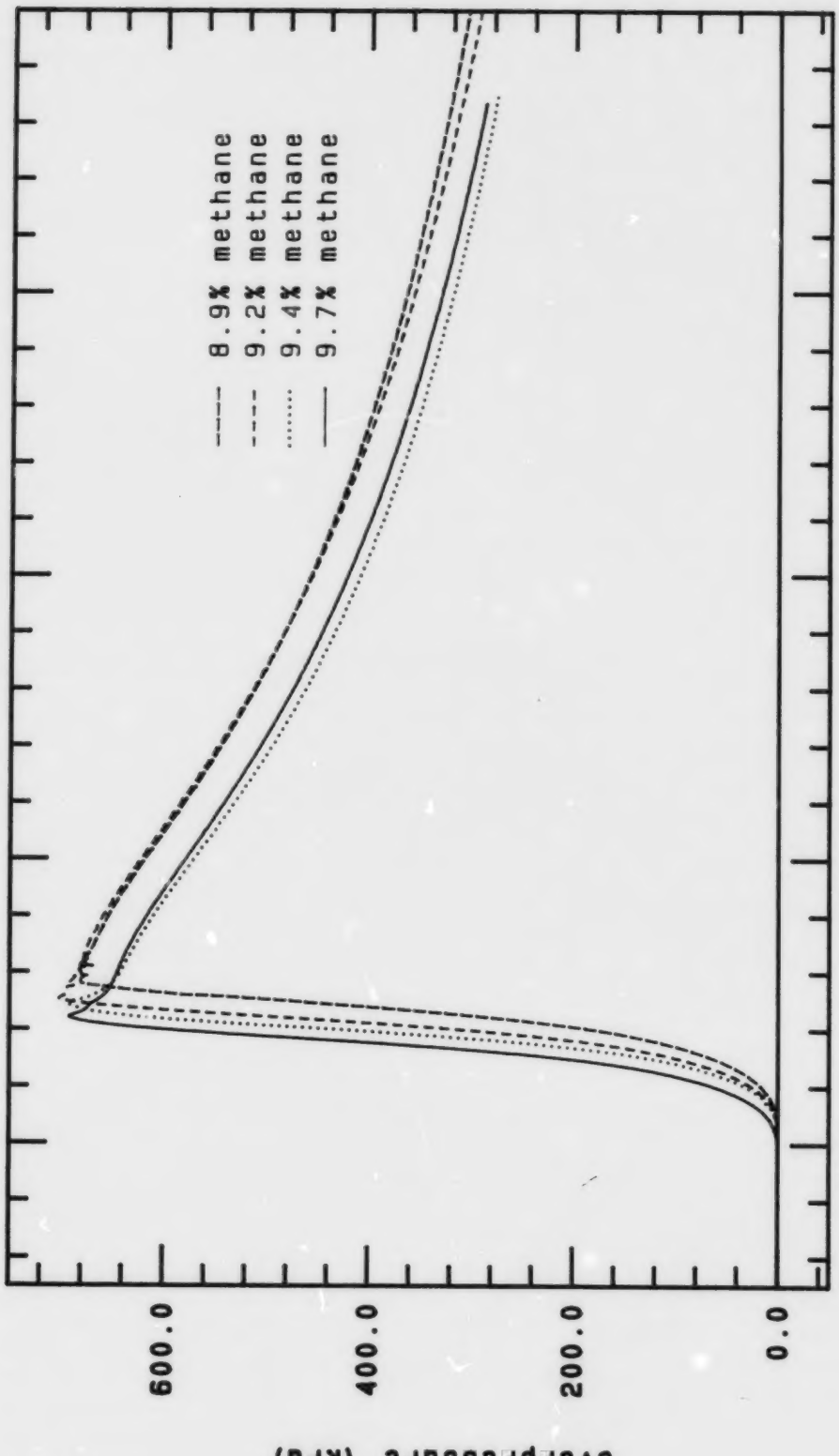
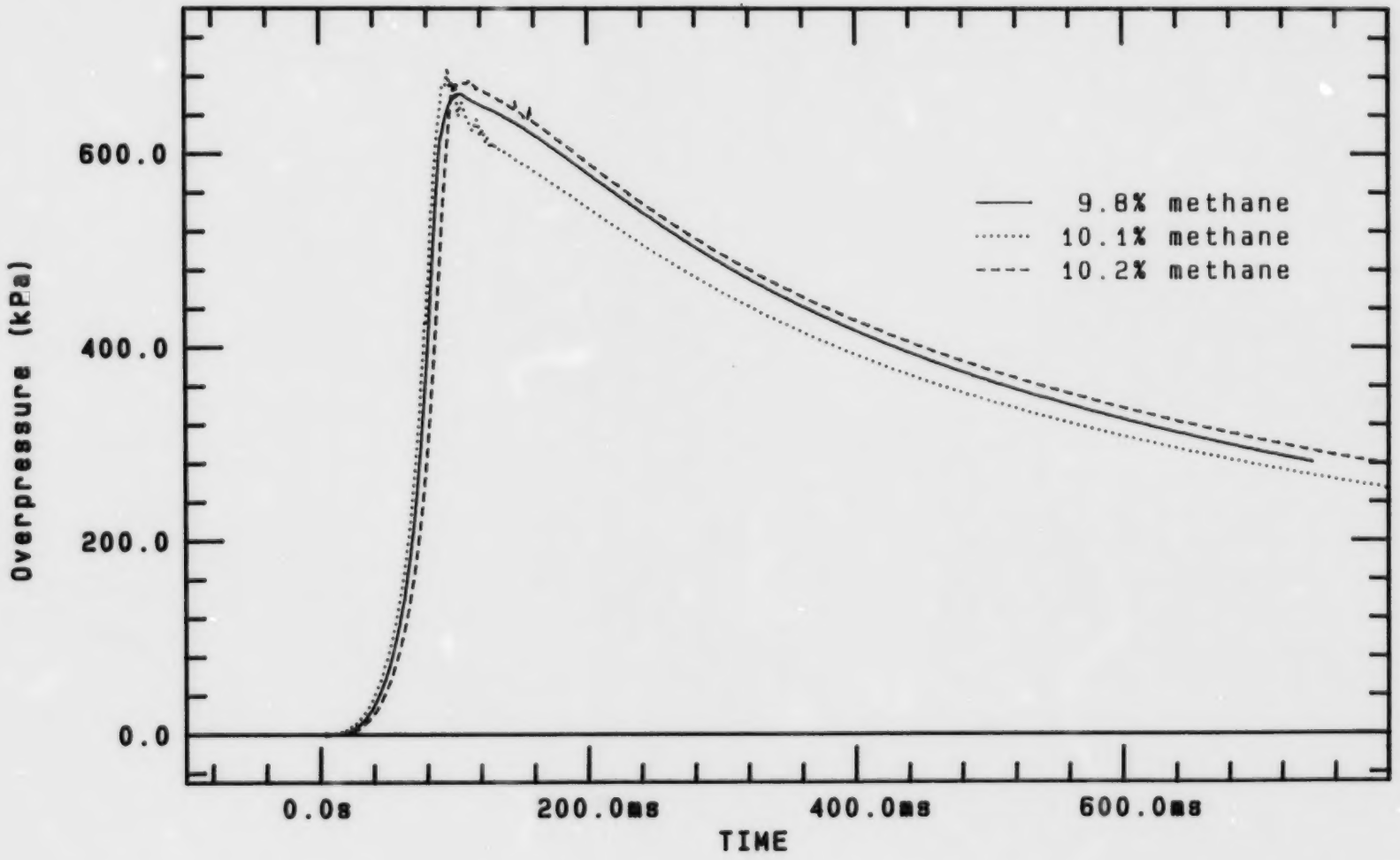


Fig.4. Pressure Traces for Methane-Air Explosions:

Fig.5. Pressure Traces for Methane-Air Explosions:

Arc Ignitor Used



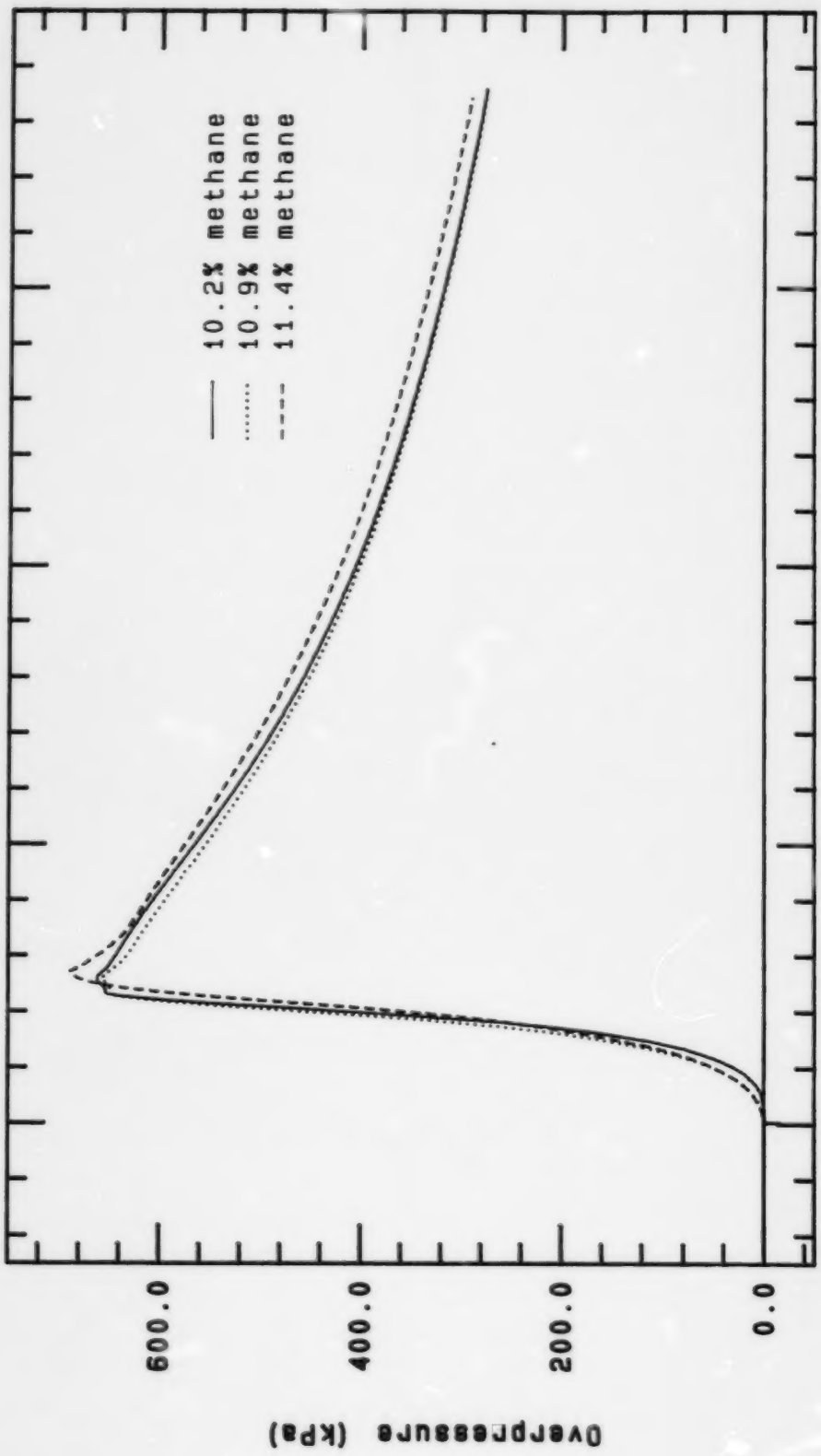


Fig.6. Pressure Traces for Methane-Air Explosions:

Arc Ignitor Used

Fig.7. Explosion Pressure of Methane: Spark Ignition, Quiescent Mixture

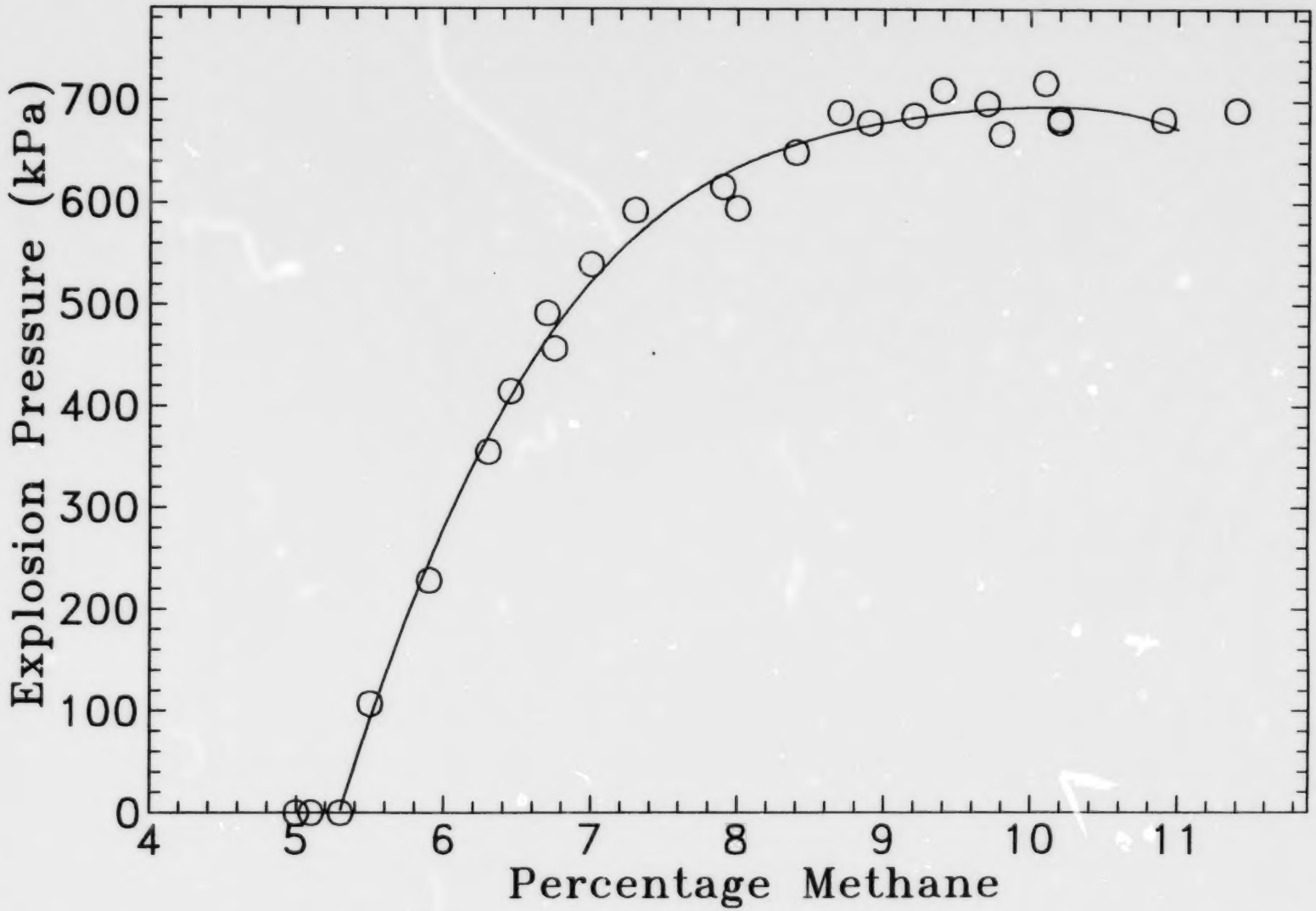


Fig.6. Derivative of Pressure Trace

For 5.5% Methane

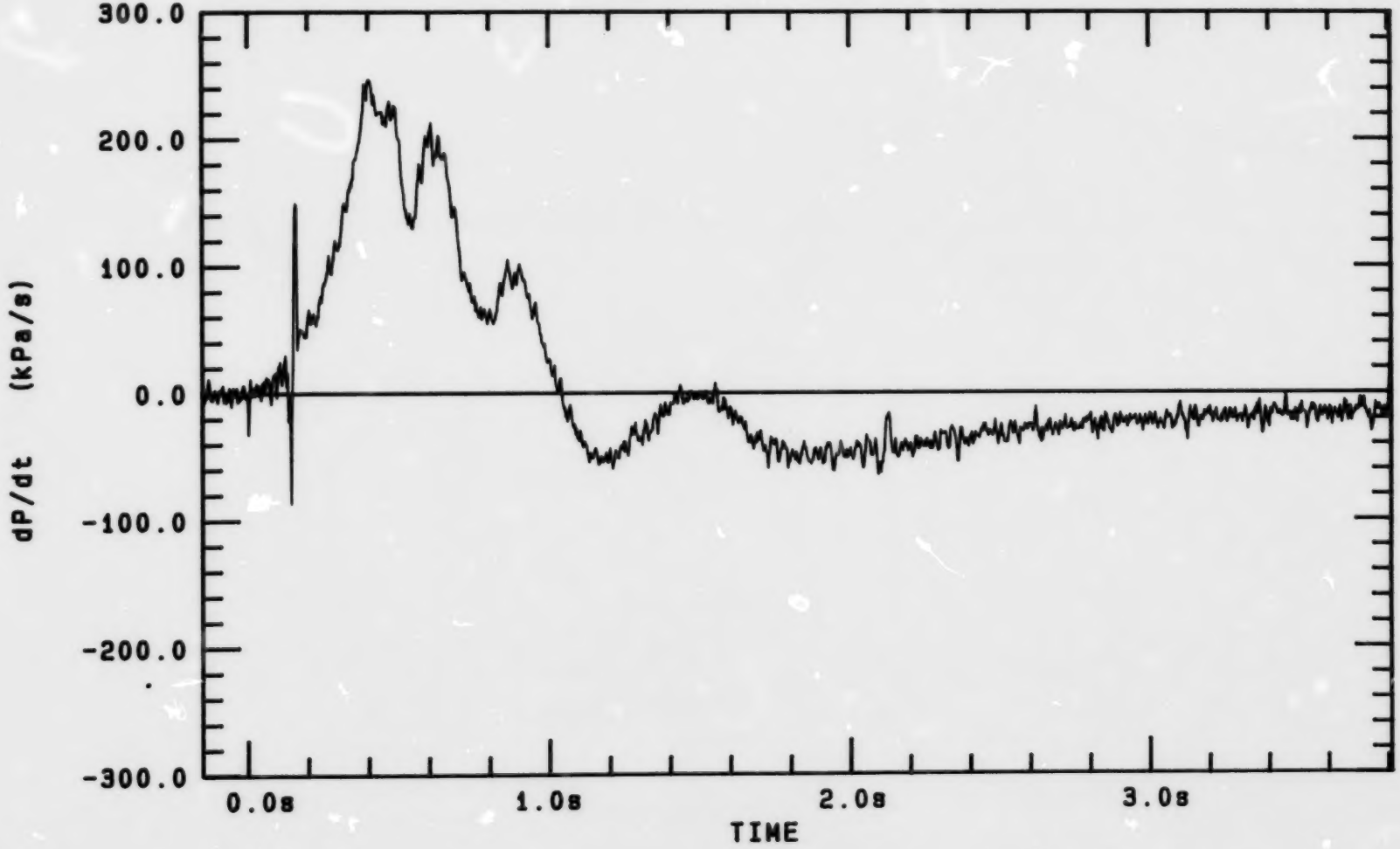
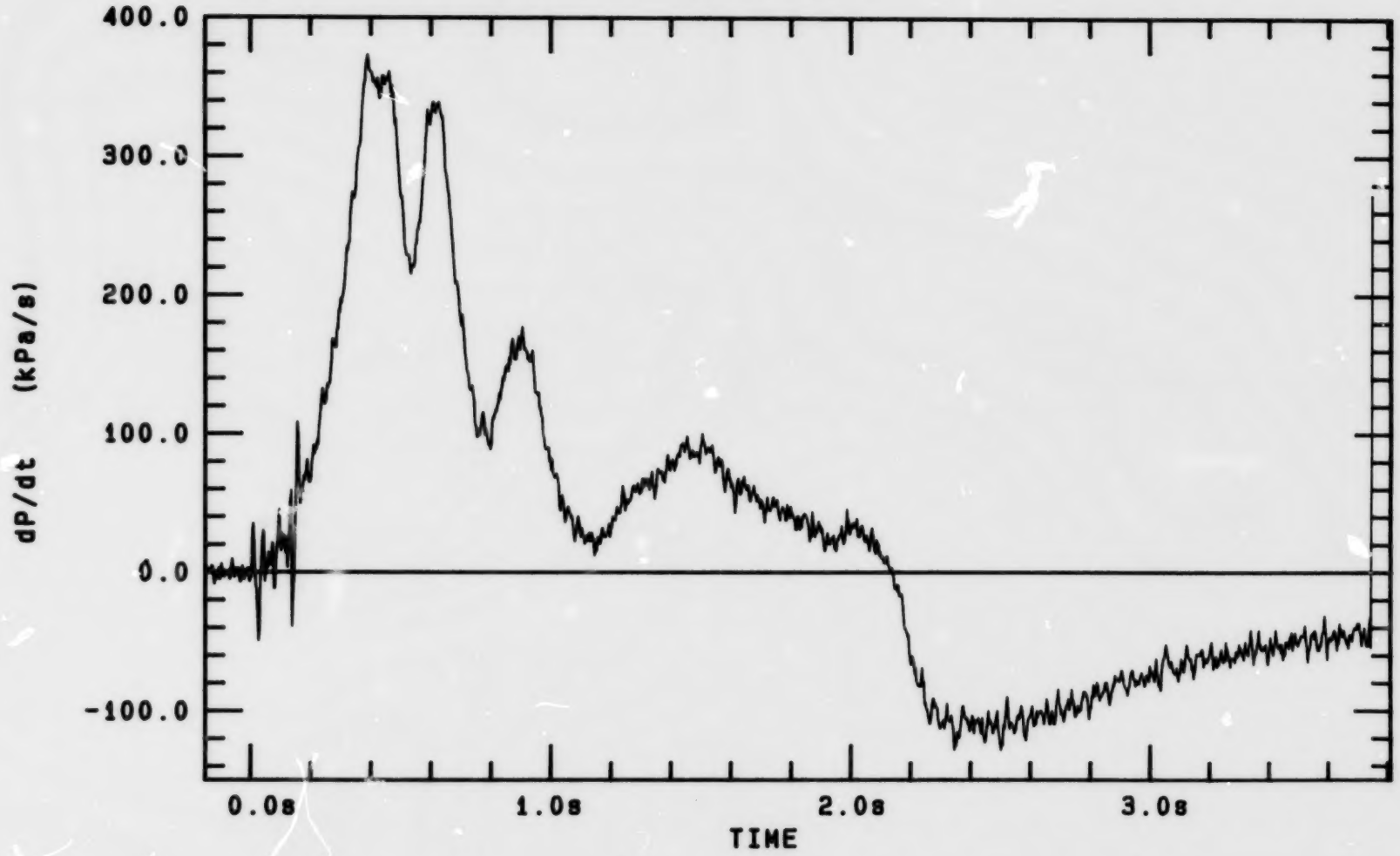


Fig.9. Derivative of Pressure Trace

For 5.9% Methane



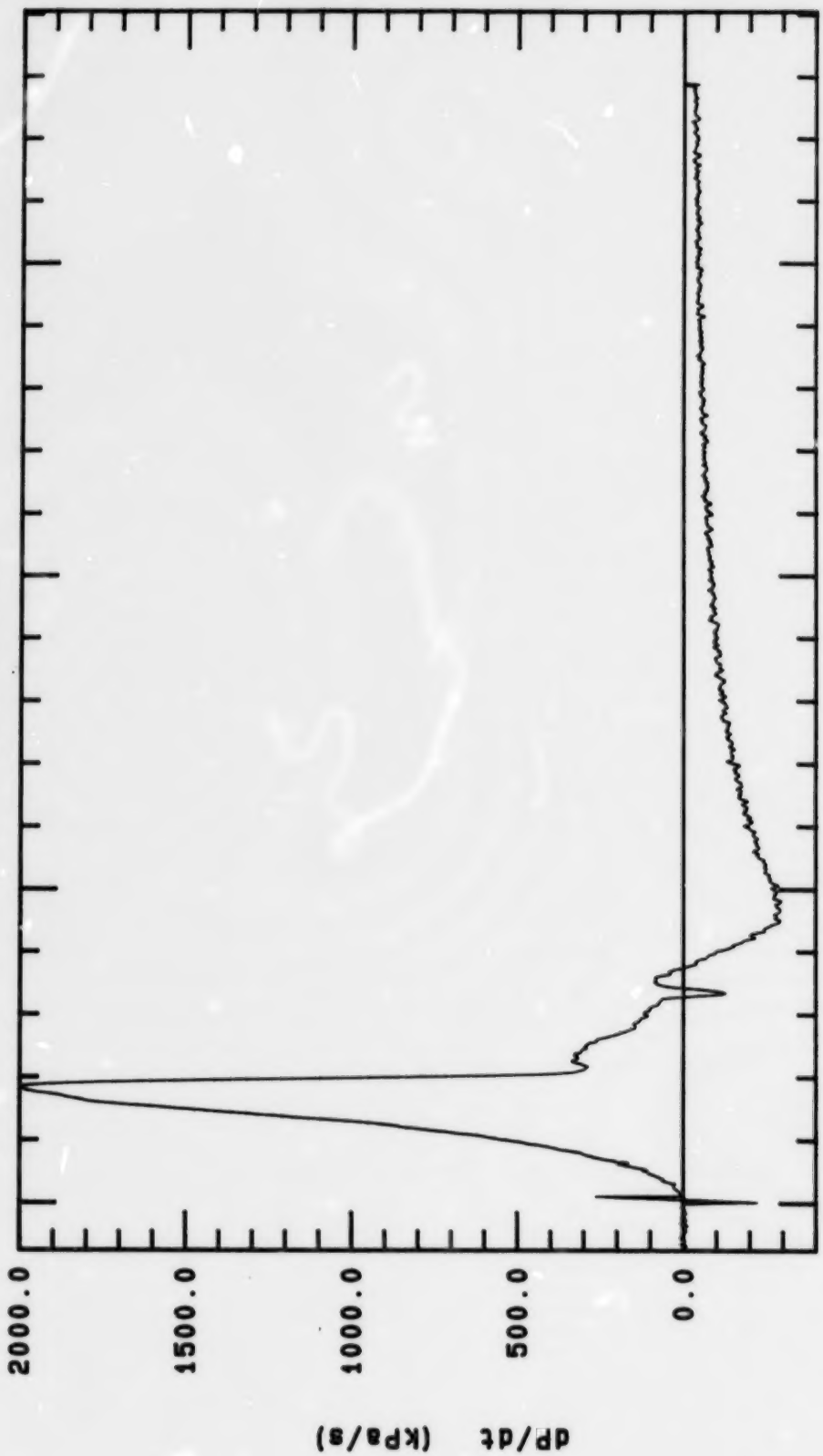


Fig.10. Derivative of Pressure Trace

For 6.3% Methane

Fig.11. Derivative of Pressure Trace

For 9.2% Methane

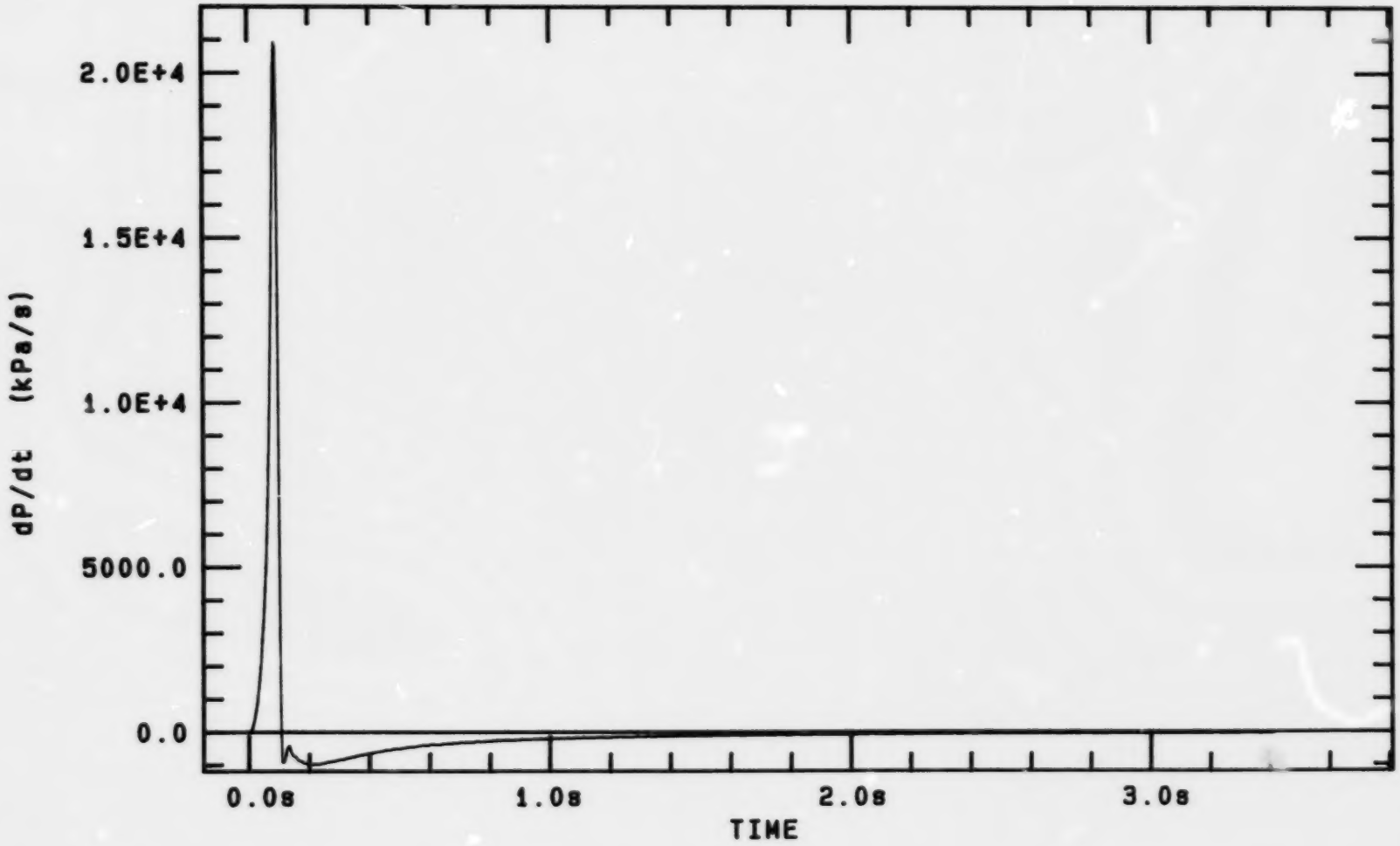


Fig.12. Rate of Pressure Rise: Spark Ignition in Quiescent Mixture

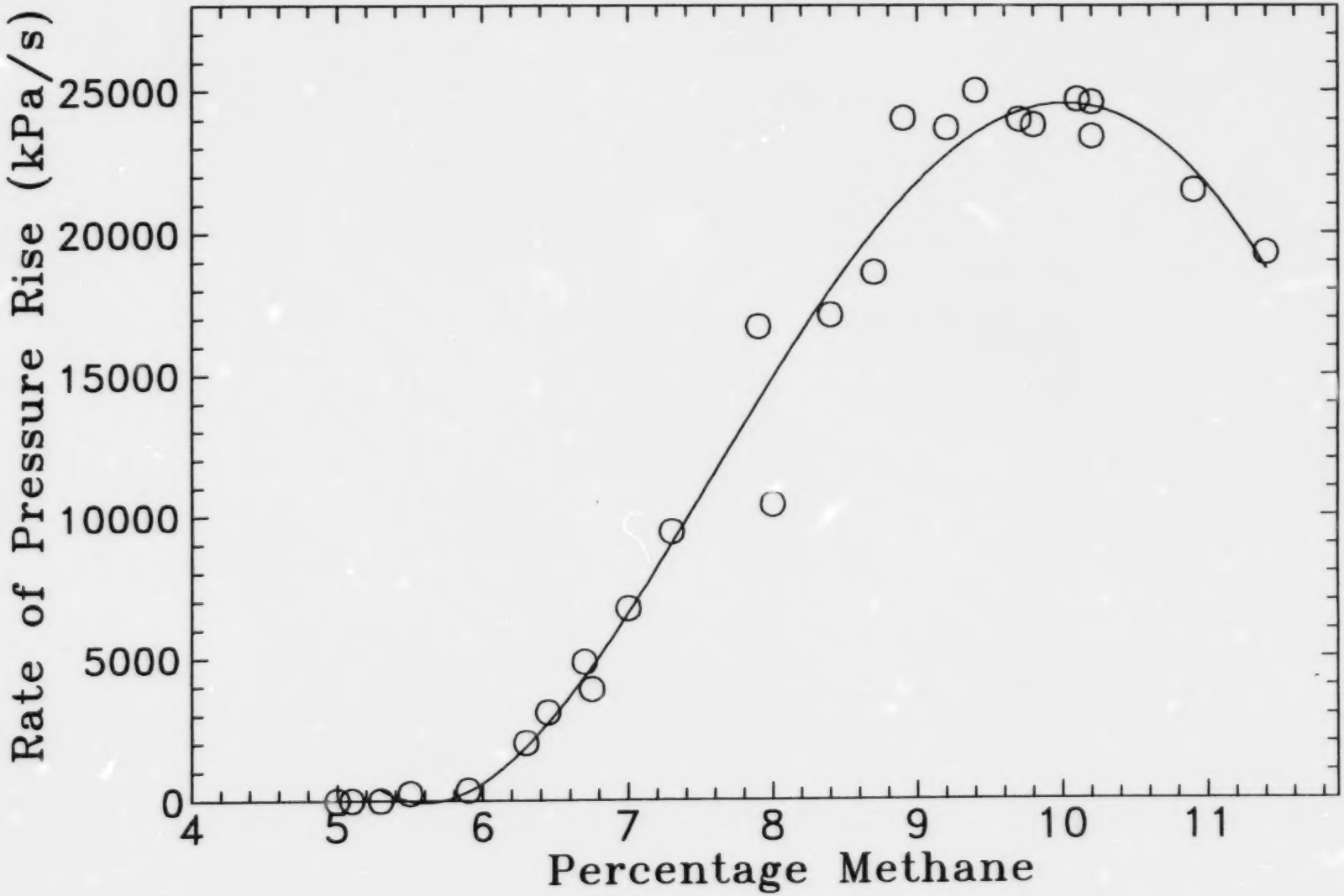


Fig.13. Temperature Rise: Spark Ignition in Quiescent Mixture

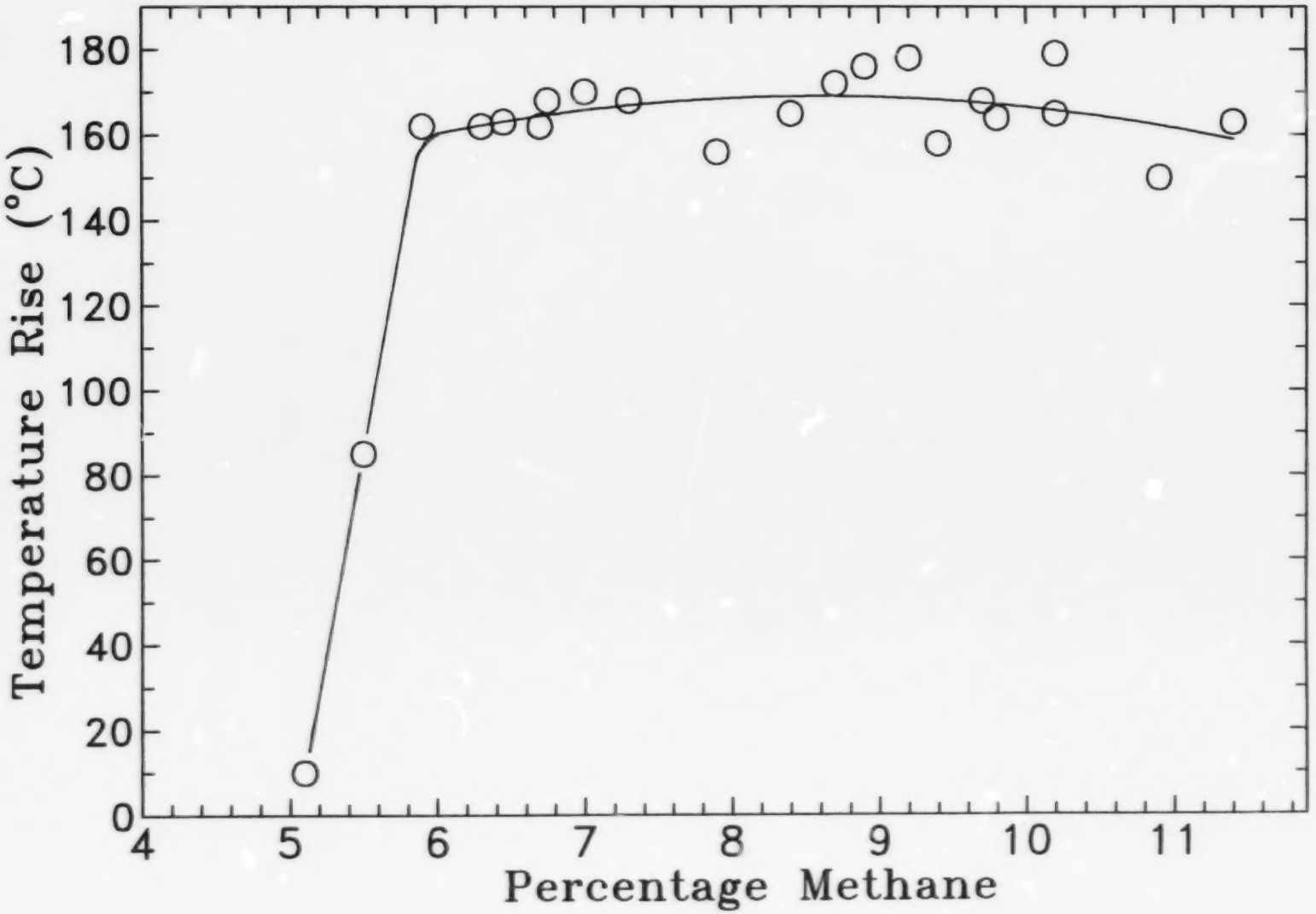


Fig.14. Pressure Traces for Methane-Air Explosions

250-J Sobbe Ignitor

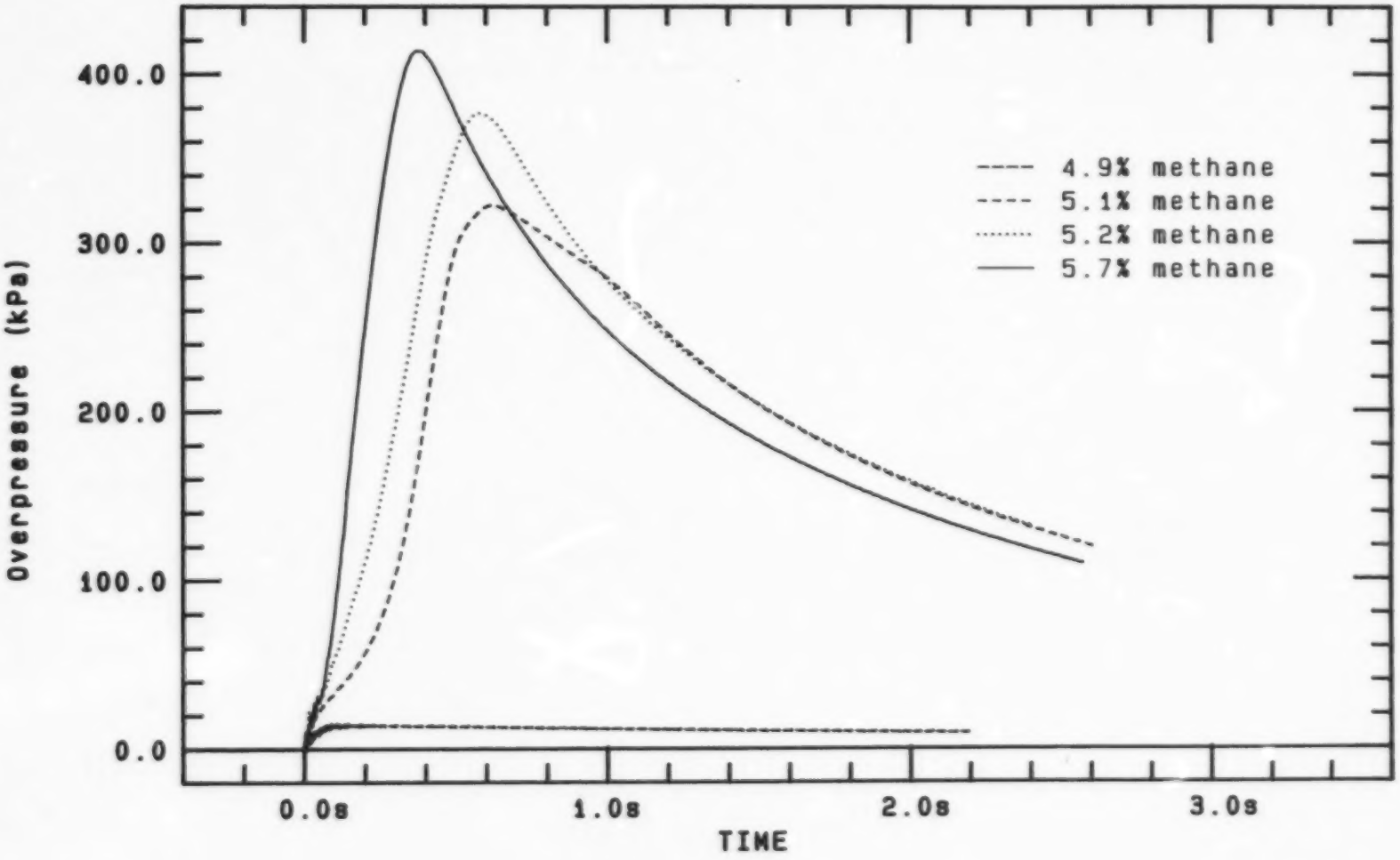


Fig.15. Pressure Traces for Methane-Air Explosions

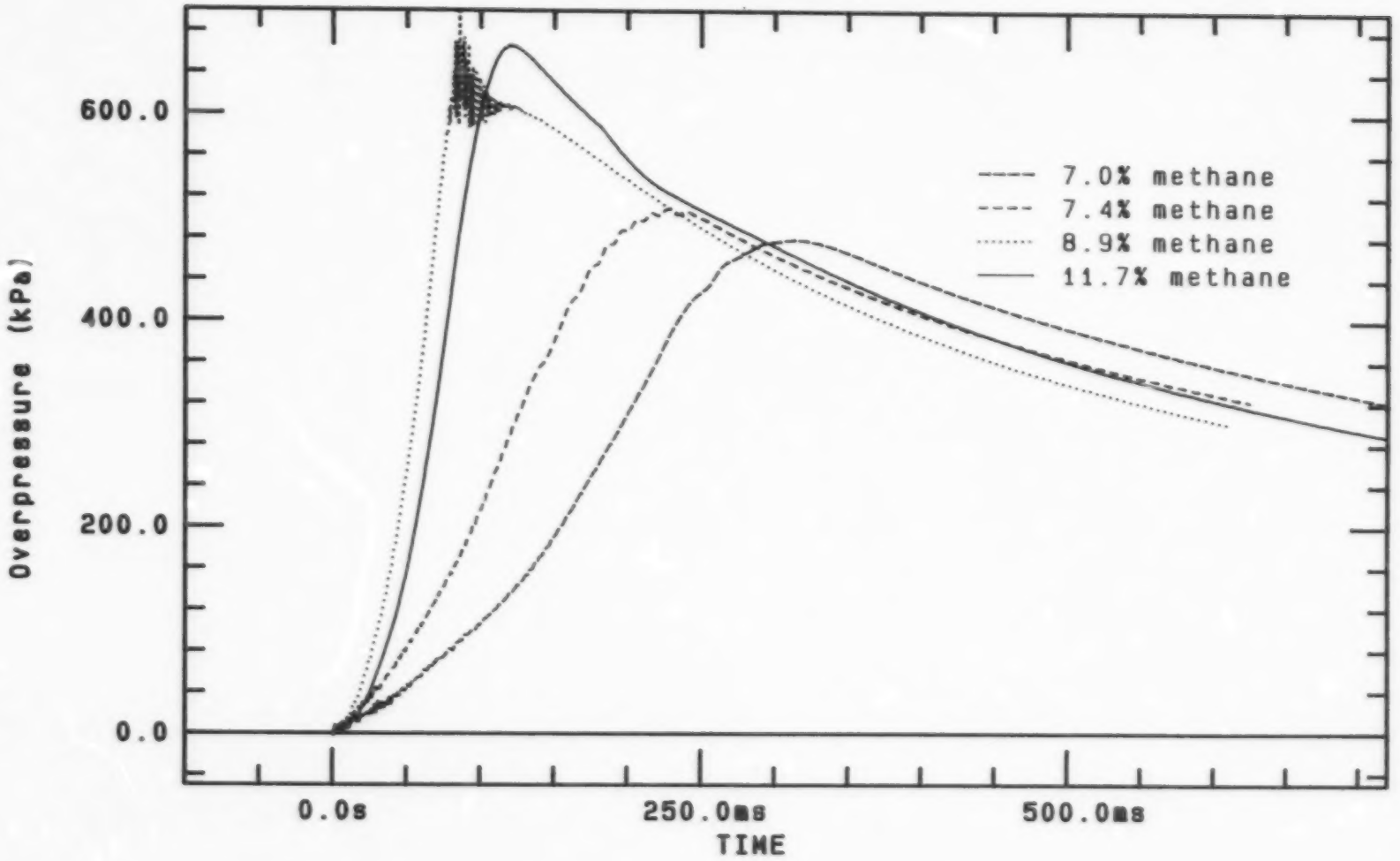


Fig.16. Derivative of Pressure Trace: 5.7% Methane

250-J Sobbe Ignitor

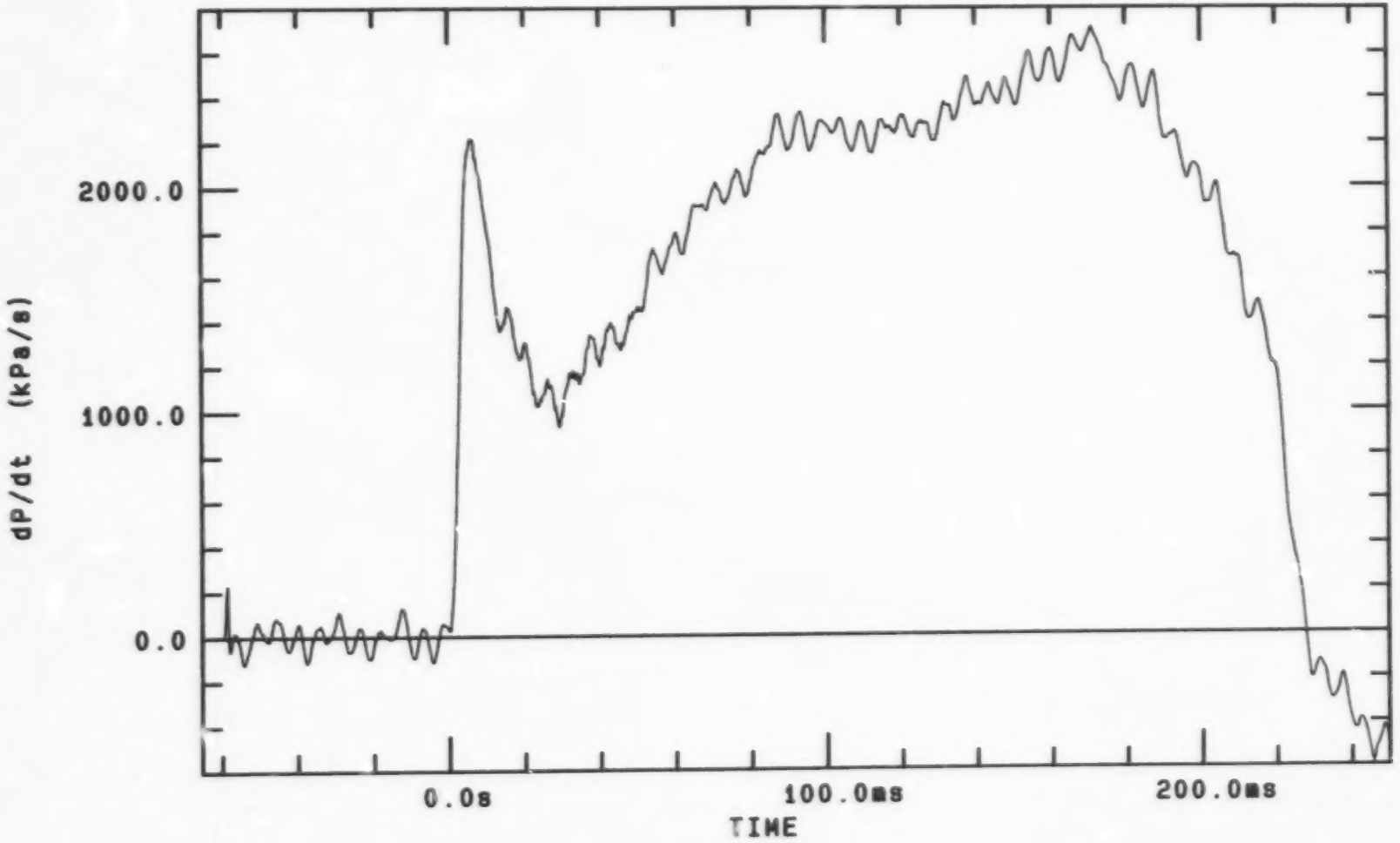


Fig.17. Explosion Pressure: Pyrotechnic Ignitor in Quiescent Mixture

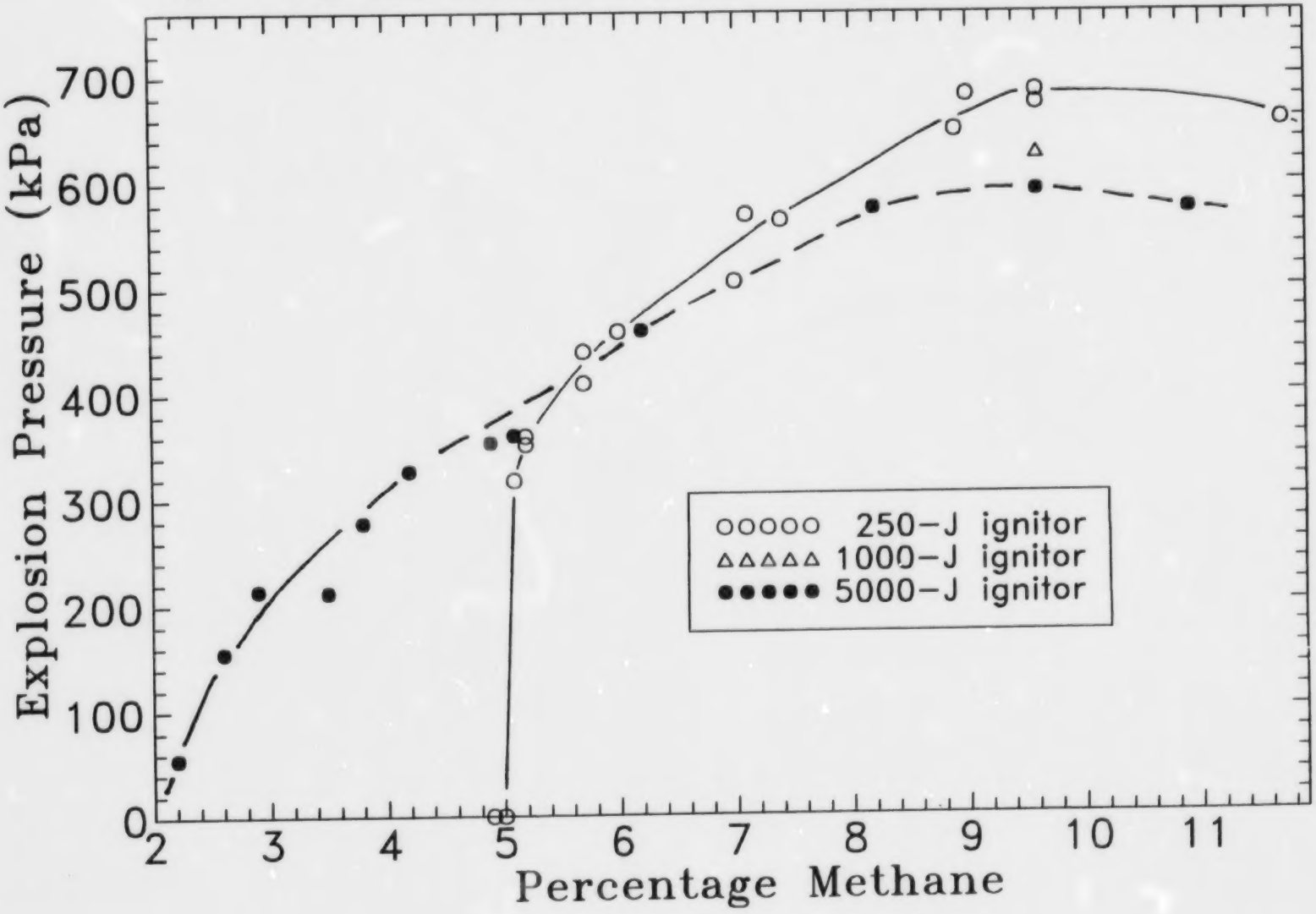


Fig.18. Rate of Pressure Rise: Pyrotechnic Ignitors in Quiescent Mixture

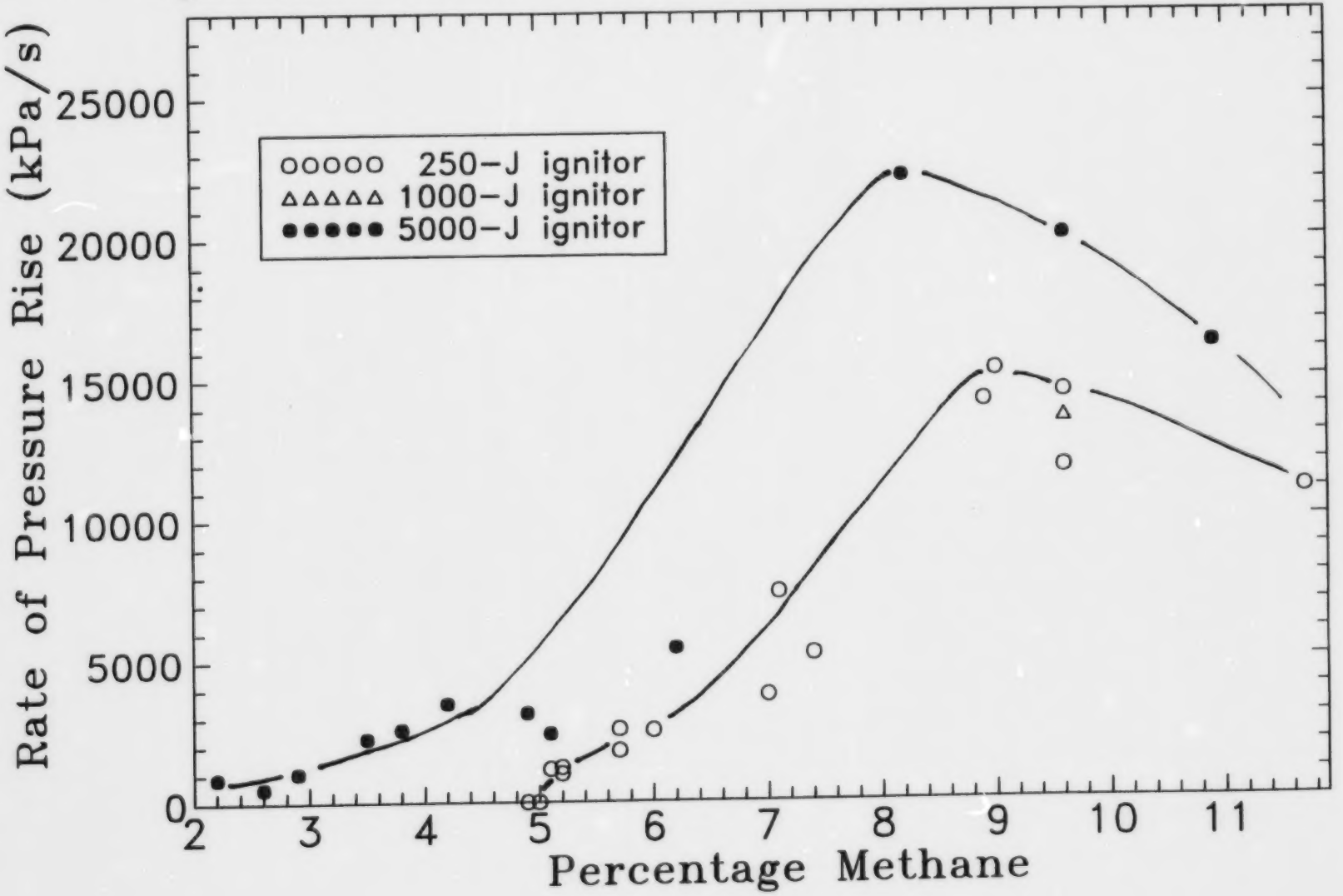


Fig.19. Pressure Traces for Methane-Air Explosions

5000-J Sobbe Ignitor

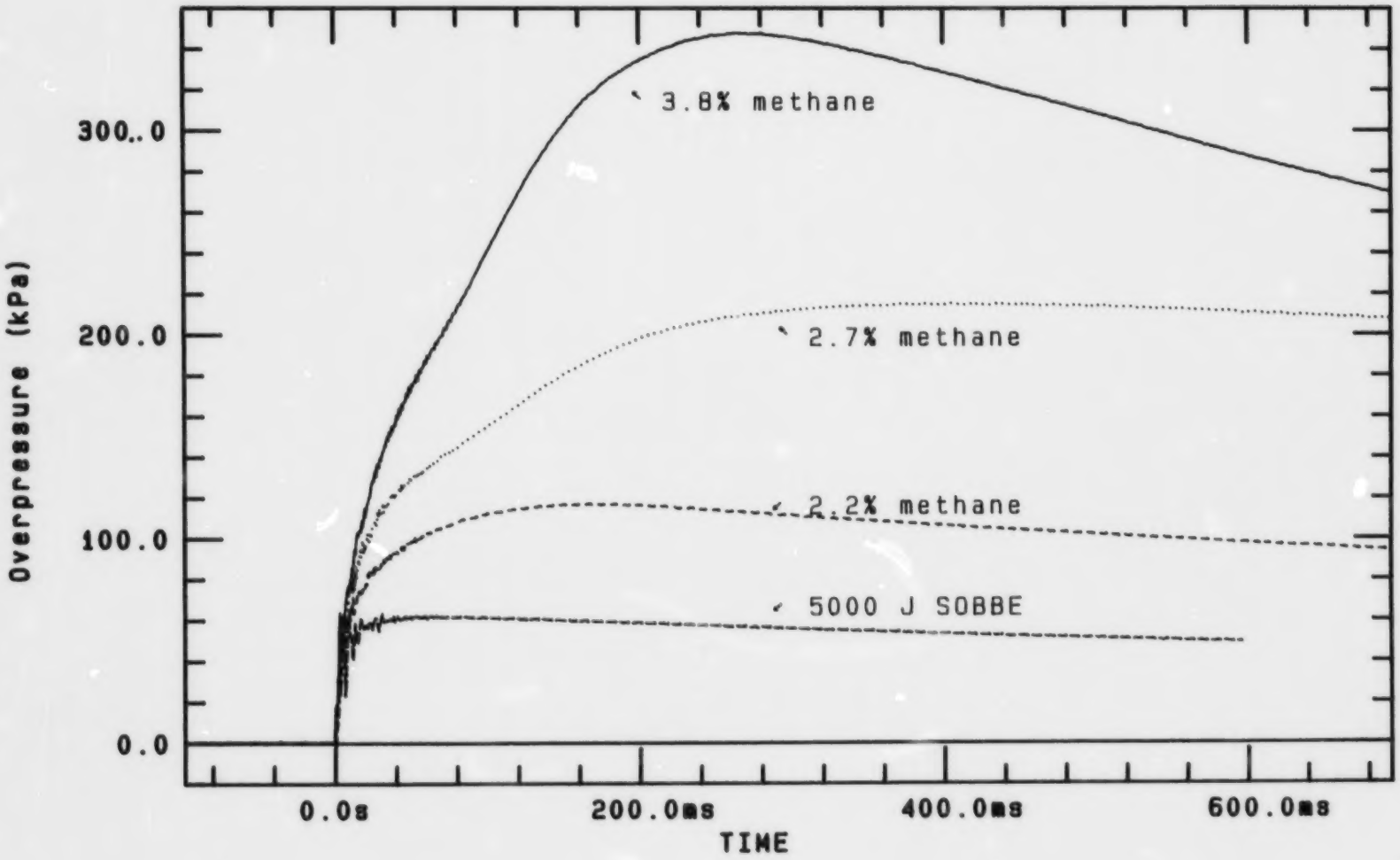


Fig.20. Temperature Rise: Pyrotechnic Ignitors in Quiescent Mixture

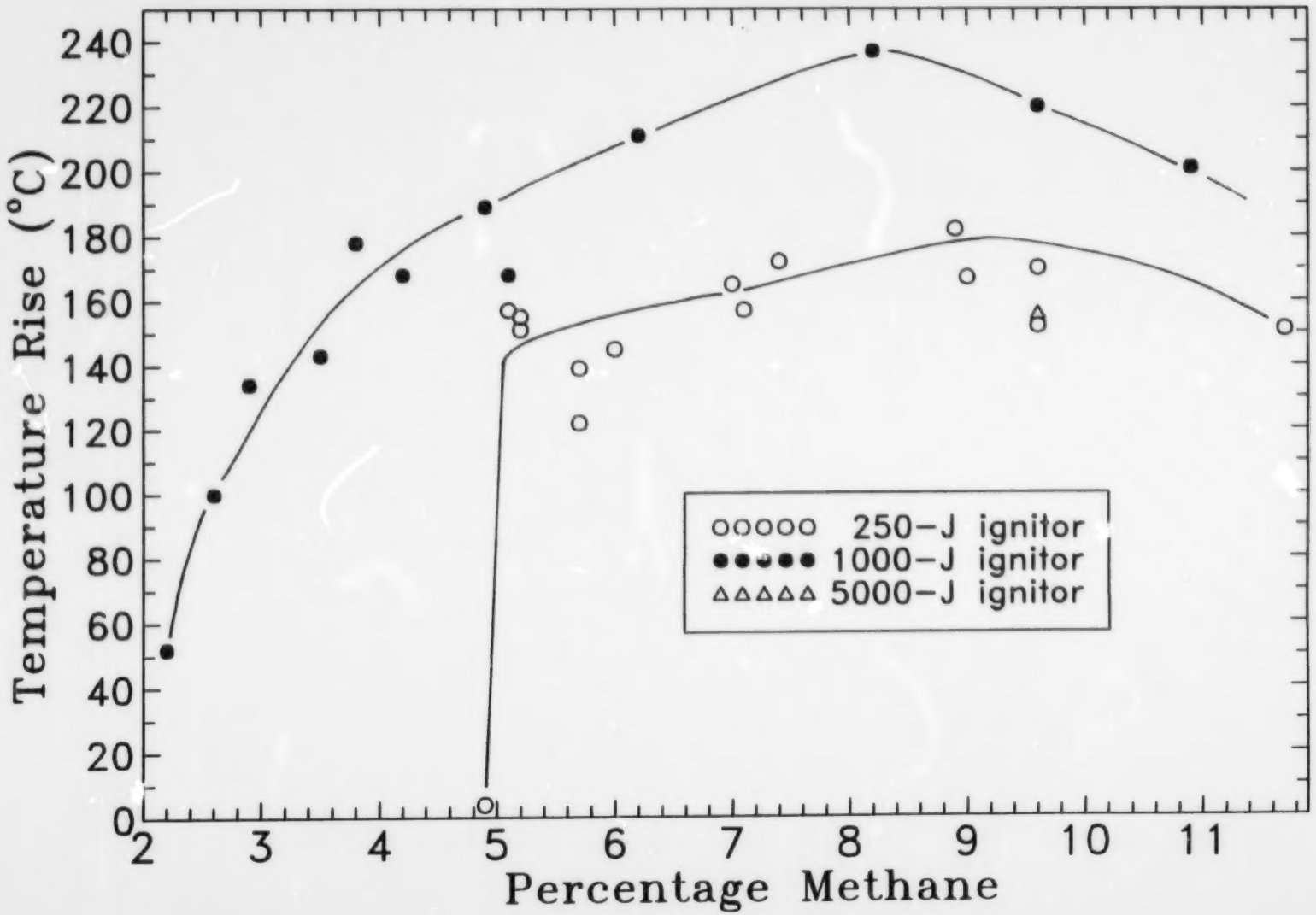


Fig.21. Oxygen Consumed: Pyrotechnic Ignitors in Quiescent Mixture

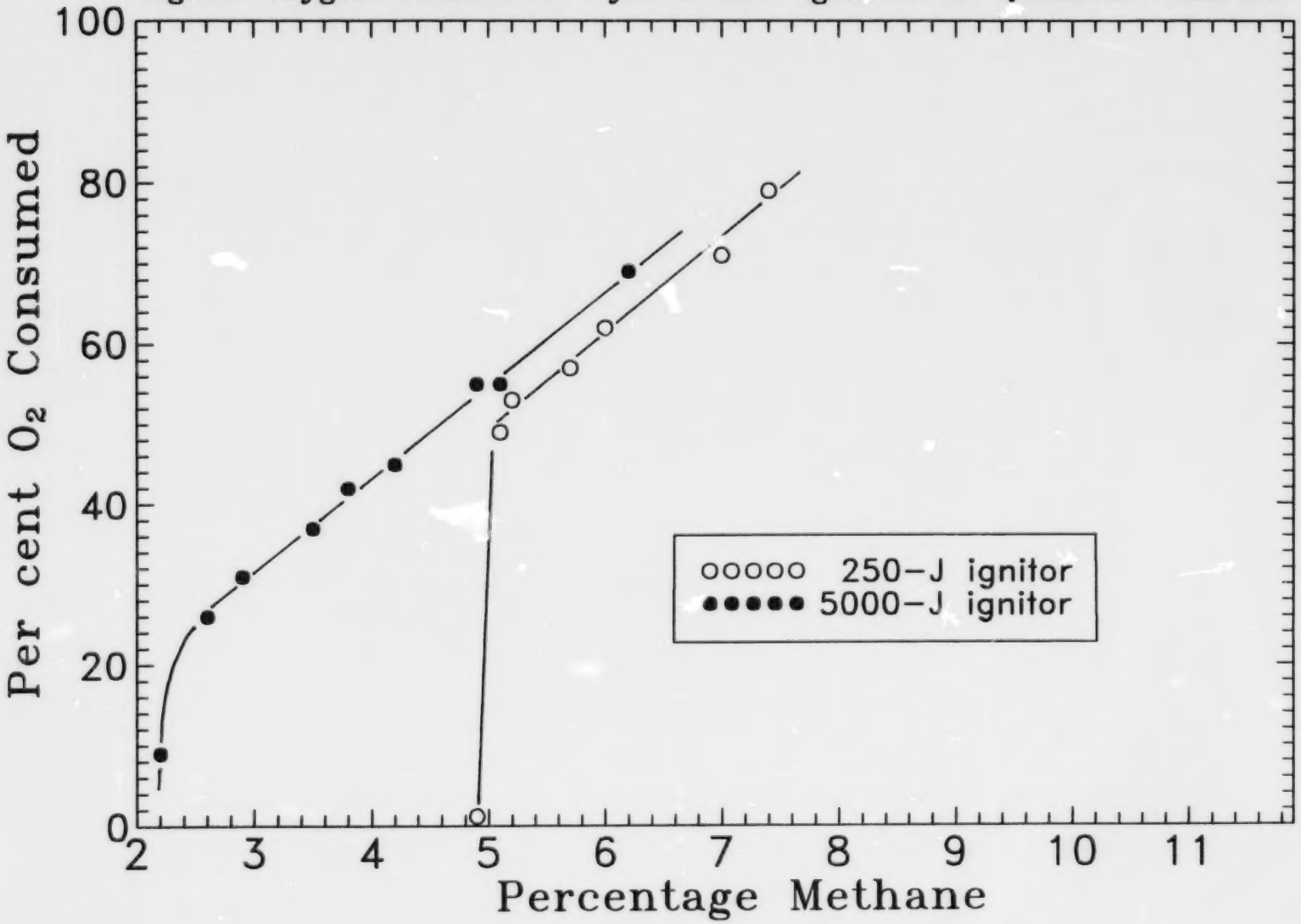


Fig.22. Correction Factor as a Function of P_{air}

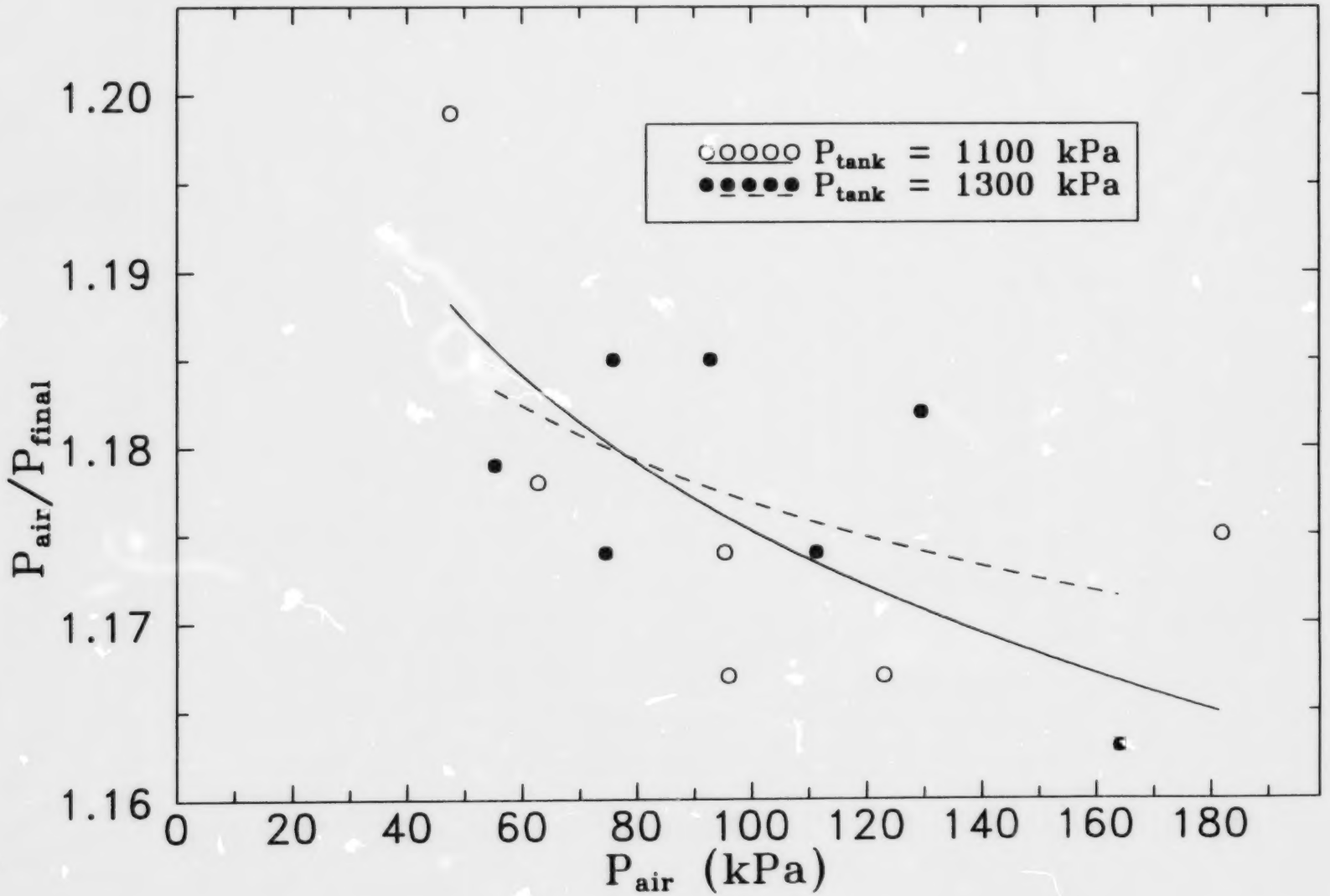


Fig.23. Explosion Pressure vs. Delay to Ignition

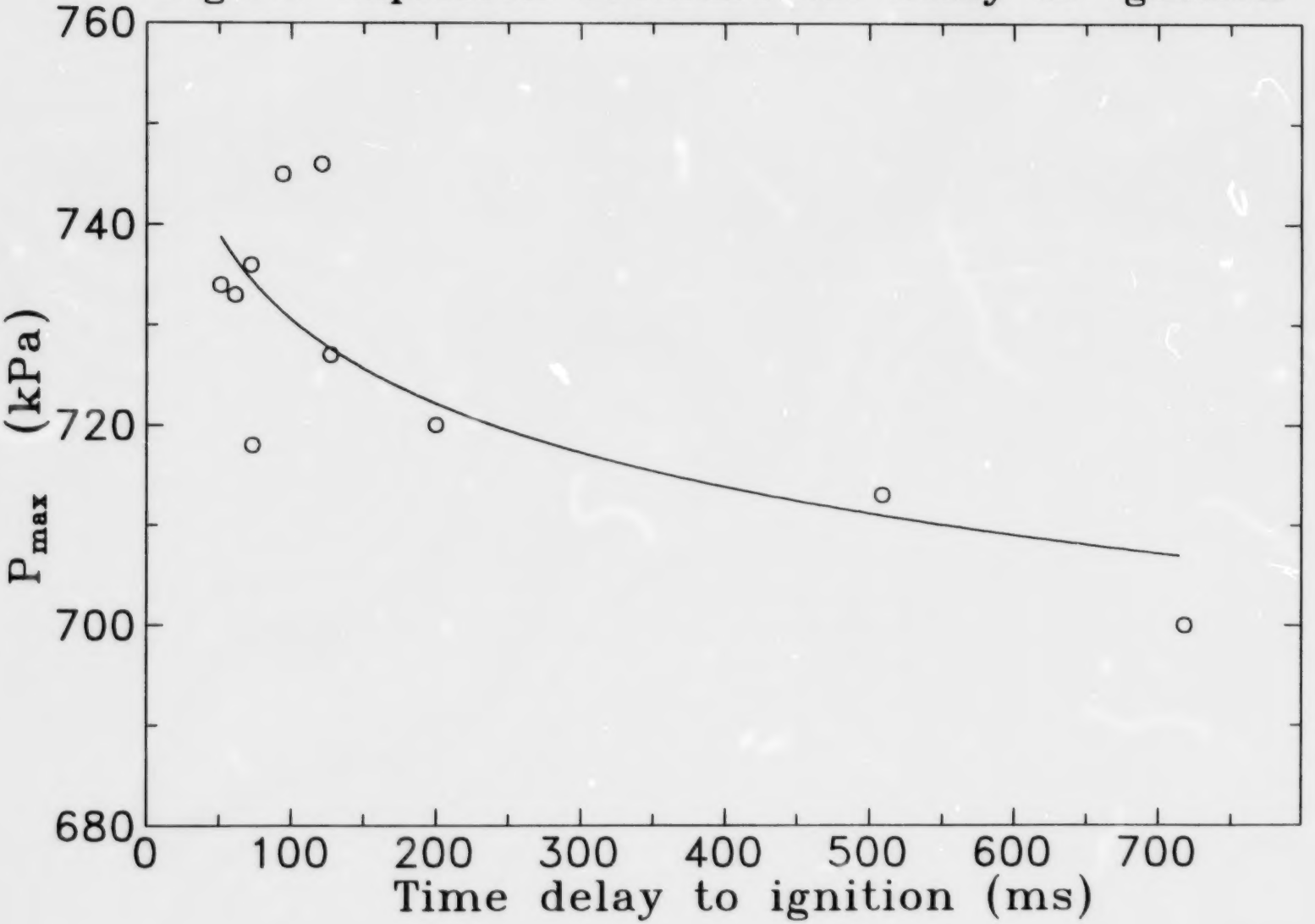


Fig.24. Rate of Pressure Rise vs. Delay to Ignition

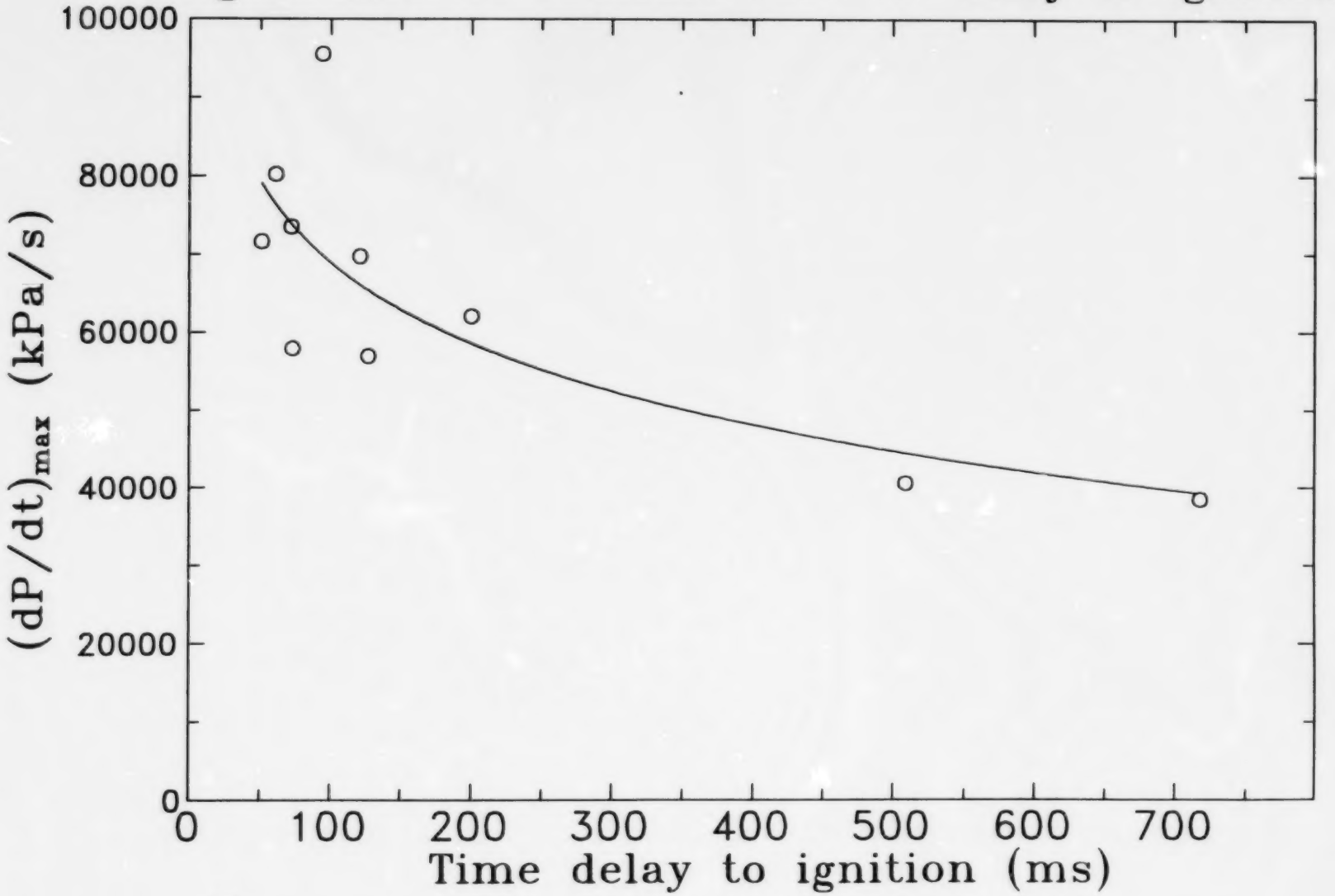


Fig.25. Explosion Pressure vs. Concentration of Methane

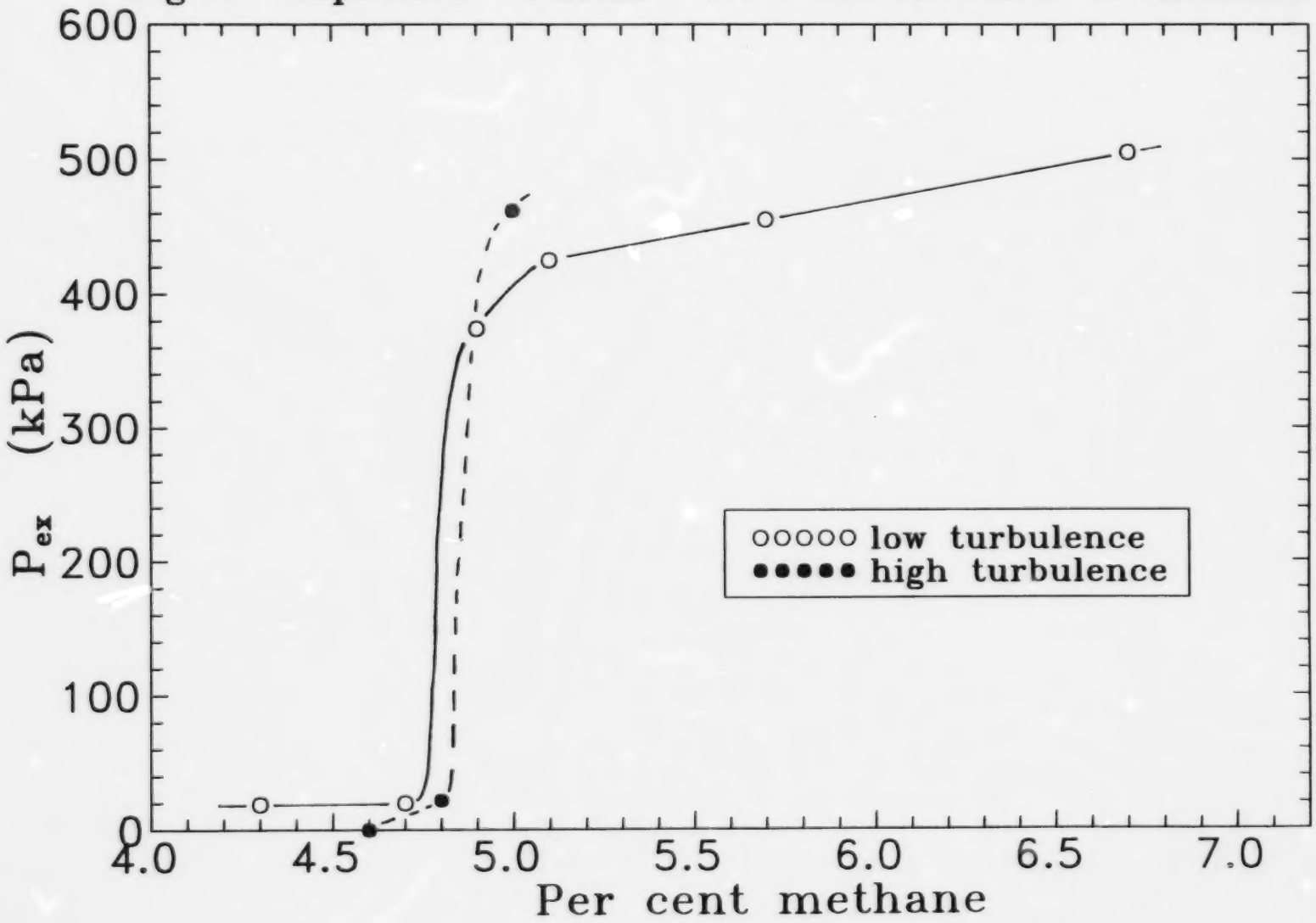


Fig.26. Rate of Pressure Rise vs. Concentration of Methane